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CHLORINATION OF MIXED SEWAGE AND STORM WATER[a]

By Thomas R. Camp,[1] F. ASCE

SYNOPSIS

Current emphasis by pollution control agencies on primary treatment of sewage as a minimum diverts attention from the primary health problem of destroying pathogens in sewage and, in some cases, results in waste of public funds. Chlorination of all sewage including that mixed with storm water is required for effective pathogen kill. Experiments indicate that screening and chlorination of raw sewage and storm water will be effective and relatively inexpensive.

INTRODUCTION

In the abatement of pollution of our water courses by municipal sewage, most of our attention has been directed during the past few decades towards the removal from sewage of suspended solids and BOD, the improvement of processes therefor and for the handling of the sludge resulting therefrom. Since about 1940 most state pollution-control agencies have been empowered to enforce pollution abatement. As a part of the enforcement process, many have adopted minimum requirements of primary sedimentation with secondary treatment required where BOD removal is an important problem. In 1956 the passage of Public Law 660 empowered the United States Public Health Service (USPHS) to make grants-in-aid for the construction of sewage works. In implementing this act, the USPHS established rules and regulations

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[a] Presented at the October 1960 ASCE Convention in Boston, Mass.

[1] Camp, Dresser & McKee, Cons. Engrs., Boston, Mass.

that require treatment to remove, substantially, 100% of settleable solids as a minimum for eligibility for a grant-in-aid.

These developments all tend to have the force of law compelling primary settling whether or not it is needed or appropriate to accomplish the required result in the receiving waters, and they divert attention from the much more important reason for sewage treatment, which is the destruction of pathogenic bacteria and viruses. Sewage solids and BOD are of aesthetic significance in the receiving waters, and if their concentration is high they may result in fish kills and odors. They are, however, of little direct significance to the public health. Pathogenic bacteria and viruses contained in sewage are, on the other hand, of the utmost importance to the public health. The author is aware of the pressure by the USPHS to have us provide even more than complete treatment of sewage so as to remove dissolved solids and exotic organics, but the evidence is not yet available that these substances are a sufficient hazard to warrant the high cost of removal. Moreover, it may be found that the best solution for the more toxic substances is to prohibit or control their use. Each pollution problem should be solved on its merits to accomplish the required result in the receiving waters at the least cost, and the public health should be paramount in all solutions.

Normal municipal sewage contains from about 50 million to about 150 million coliform bacteria per 100 ml (milliliters). The number of coliform bacteria in the receiving waters is an index to the probability of the presence of pathogens and therefore to the safety of the water for human use. For the safe use of the receiving waters for swimming or recreation, the coliform count in the receiving waters should not exceed approximately 1,000 per 100 ml. Such a water is also bacteriologically suitable for drinking after treatment by rapid filtration and chlorination.

It is of no significance whether the safe standard for swimming is set at 240 or any other figure up to about 3,000 because a reduction of approximately 99.999% must be accomplished to meet the standard, and the difference in the required reduction within these limits for the standard is less than 0.003% . If a reduction of 99% is effected by dilution with the receiving waters, the treatment plant must effect a bacterial kill of at least 99.9%. If a reduction of 99.9% is effected by dilution with the receiving stream, the treatment plant must effect a bacterial kill of at least 99%. The conventional sewage treatment processes of primary settling and BOD removal are of no significance in this objective since both primary and complete treatment are erratic in removal of coliform bacteria and cannot be relied upon to reduce the coliform count by a significant amount (99% or more). Adequate chlorination is essential for effective coliform reduction, and, as shown hereinafter, it will also inactivate pathogenic viruses.

Some real examples of unnamed municipalities will serve to illustrate the economic waste resulting from misplaced emphasis on primary settling rather than bacterial removal. One small municipality with a design population of 7,560 people discharges its sewage, untreated, through a system of combined sewers into a stream with a critical minimum flow of 1,000 cfs. At an average contribution of 200 billion coliforms per person per day, the average increase in MPN (most probable number) in the receiving stream is 60,000 per 100 ml. The required average removal of bacteria to reclaim this stream for swimming is 98.5%. In order to attain this objective, all of the sewage must be chlorinated, including that mixed with storm water during rainstorms.

At 0.2 lb per capita per day for BOD and for suspended solids, the average increase in suspended solids and in BOD in the receiving stream during dry weather is only 0.28 ppm.

With 60% removal of suspended solids by primary treatment, the resulting increment to the receiving stream is only 0.11 ppm. Since the suspended solids content in the river upstream from the point of pollution resulting from natural causes ranges from 8 ppm to 16 ppm, it should be obvious that primary treatment of the dry weather flow will serve no useful purpose. The BOD of the receiving stream upstream from the point of pollution is generally less than 2 ppm and the dissolved oxygen content is from 6 ppm to 10 ppm. There is, therefore, no BOD problem in this stream at the point of pollution. If there are unsightly discharges of sewage into the stream from visible sewer outlets, these may be almost completely eliminated by screening and by extending the outlet sewer to discharge submerged under low water at several points.

Another small municipality with a design population of 9,000 discharges its sewage untreated through a system of combined sewers into a large stream with a critical low flow of 600 cfs. Upstream from the point of pollution this stream is clear and contains a negligible BOD. The computed increment of coliform bacteria at the point of pollution during dry weather is 120,000 per 100 ml. The required removal of coliform bacteria to make the stream safe for swimming is slightly greater than 99%. In this case, the suspended solids and BOD contribution from the raw sewage to the stream during dry weather is approximately 0.56 ppm. Here again primary treatment of the sewage will serve no useful purpose, but all of the sewage, including that mixed with storm water, must be chlorinated to reclaim the stream for swimming.

Cases of this sort are not confined to small municipalities. A large metropolitan community with a population of about three million discharges its sewage from combined sewers after primary treatment of the dry weather flow into a large stream with a minimum flow of about 100,000 cfs. The coliform contribution from the raw sewage is estimated at an average of 246,000 per 100 ml of stream water. In order to meet a standard of 1,000 per 100 ml, a bacterial kill of 99.6% is required. The contribution of suspened solids to the stream from the raw sewage from this metropolitan area is estimated at 1.1 ppm, and the BOD is approximately the same. It is evident that primary treatment of the sewage from this area is of little real value. This stream is used for water supplies downstream from the point of pollution, and effective bacterial removal is, therefore, very desirabe.

MIXED SEWAGE AND STORM WATER

Most of the older American municipalities, both large and small, have combined sewer systems, in the older portions of the community, that receive both sanitary sewage and storm-water runoff. For reasons of economy, only the peak dry weather flow can be intercepted for treatment, and mixed raw sewage and storm water are discharged to the receiving waters during rainstorms. It has long been known that this method of solution of the problem accomplishes the collection for treatment of about 97% of the years's production of sanitary sewage with only about 3% going overboard during rainstorms. It has been tacitly assumed that effective chlorination of the dry weather flow at the treatment works is an effective protection to the receiving water. This is usually not the case, because, with 3% of the sewage

going overboard during rainstorms, the average bacterial reduction cannot exceed about 97% even with 100% kill by chlorine. The previously described examples indicate that 97% average reduction is usually not sufficient. Moreover, during rainstorms gross bacterial pollution takes place.

In studies by J. E. McKee[2] in 1946, based on Boston, Mass., rainfall records, it was shown for the first time that with interceptors and treatment plants designed for two to three times the average dry-weather flow, there would be overflows of mixed untreated sewage and storm water on 5 to 6 days of each month on the average. These studies further show that during rainfalls with intensities of only 0.05 in. per hr, approximately 60% of the sanitary sewage would be discharged overboard into the receiving stream and that during rainfalls with intensities of about 0.20 in. per hr, nearly 90% of the sanitary sewage would be discharged into the receiving stream untreated. Thus, large slugs of pollution of intestinal bacteria and viruses will be discharged to the receiving water nearly every time it rains. In the author's opinion, such waters are not safe for either bathing or recreation.

McKee's studies also showed that substantial increases in the capacity of the interceptors and treatment works would serve no useful purpose in reducing the frequency of overflows of raw sewage into the receiving waters unless the capacity is increased to that of the combined sewers. For example, with interceptors having a capacity of 20 times the dry-weather flow, overflows might be expected on one to two days per month on the average. Somewhat similar results were found by C. L. Palmer[3] in 1949 for Detroit, Mich., conditions, and similar results were reported by C. F. Johnson[4] in 1958 for the District of Columbia. The author has found similar results for rainfall data in Concord,[5] N. H., and in Bogota, Columbia.

The problem of effective reduction of coliform bacteria discharged from combined systems may be solved by either of two methods or combinations thereof. The most effective, but also the most expensive method, is to separate the existing system by constructing a complete new system so that there will be two separate systems of sewers, one for storm water and another for sanitary sewage. With this method chlorination of the sanitary sewage is all that will be required. The other method is to chlorinate all of the sewage including mixed sewage and storm water. This second method will require large capacity for chlorination plants to care for the storm water flows, but the additional amount of chlorine that will be required over and above that needed to chlorinate the dry weather flow is surprisingly small as will be shown hereinafter. The remainder of this paper deals primarily with the results of studies on the chlorination of raw sewage and mixtures of raw sewage and storm water.

BOSTON EXPERIMENTS

Ten experiments were conducted under the author's direction in October, 1959, on the chlorination of comminuted raw sewage from the Nut Island

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[2] "Loss of Sanitary Sewage through Storm Water Overflows," by J. E. McKee, Journal, Boston Soc. of Civ. Engrs., April, 1947, p. 55.

[3] "The Pollutional Effects of Storm Water Overflows from Combined Sewers," by Clyde L. Palmer, Sewage and Industrial Wastes, February, 1950, p. 154.

[4] "Nations Capital Enlarges its Sewerage System," by C. Frank Johnson, Civil Engineering, June, 1958, p. 56.

[5] "Overflows of Sanitary Sewage from Combined Sewerage Systems," by Thomas R. Camp, Sewage and Industrial Wastes, April, 1959, p. 381.

Sewage Treatment Plant in Metropolitan Boston with chlorine doses ranging from 20 ppm to 38 ppm. These experiments were conducted during a period when the sewage contained very little storm water. The chlorine demand in these tests after about 2 min increased slightly with time of contact and ranged among the tests from about 4 ppm to 23 ppm. The chlorine dose necessary to maintain a 10 ppm combined chlorine residual for 1 hr, required for virus inactivation as shown hereinafter, ranged from 12 ppm to 34 ppm and averaged 25 ppm. The coliform count in the raw sewage in terms of the MPN ranged from 43 million to 150 million per 100 ml.

Most of these tests were made in a model chlorine contact chamber which was 2 ft square in plan and had a 2 ft depth of sewage. The chamber was equipped with a vertical draft tube in the center with a propeller at the top to circulate the sewage downward and radially outward at the bottom. The power dissipation in the sewage at the maximum speed of the propeller of about 3,200 rpm was about 4.12 ft-lb per sec per cu ft of tank, and the turnover period was about 2 min.

The model contact chamber was operated on the fill and draw basis with contact periods measured from the time of introducing the chlorine. Samples of the comminuted raw unchlorinated sewage were collected for bacterial examination, and samples of the chlorinated sewage were collected for coliform counts after 2 min, 5 min, 10 min, 15 min, and 20 min, and longer periods of time. A portion of each sample collected was blended for 1 min in a Waring blender after dechlorination for comparison of the coliform count before and after blending. The purpose of this procedure was to determine the effectiveness of penetration of suspended particles by chlorine.

The results of these tests are shown in Figs. 1, 2, and 3. In all but one of these experiments, coliform kills in excess of 99.9% were achieved in less than 10 min. The coliform counts in the portions that had been blended showed an increase of 5 to 10-fold. Nevertheless, the coliform kills in the blended samples exceeded 99.9% in eight out of the ten runs at 10 min contact time. It will be noted from Figs. 1 to 3 that the coliform counts after 10 min contact time were generally in the order of 1,000 to 100,000, and in no case was the count less than 100.

In order to examine into the effect of prolonged mixing in the chlorine contact unit, samples were taken at intervals during a 90-min mixing period as shown in Fig. 3. These runs indicate a gradual decrease in coliform count with prolonged mixing in both the unblended and blended portions of the samples. Portions of the same sewage were collected in a drum and subjected to the same chlorine doses. The sewage in the drum was stirred gently at intervals throughout the 90-min period. It will be noted from Fig. 3 that the bacterial kill in the drum was substantially the same for both unblended and blended samples as the bacterial kill in the chlorine contact unit. This tends to indicate that the violence of the mix in the chlorine contact chamber was not sufficient to increase the rate and percentage kill above what might be expected with no mixing.

The two runs illustrated on Fig. 4 were conducted to determine whether pre-chlorination with a short period of settling of comminuted raw sewage would result in greater bacterial kills than can be obtained by mixing without settling. The sewage in these runs was settled in drums for a period of 12 min, during which it was subjected to chlorine doses of 20 ppm and 30 ppm. Samples were collected for bacterial analysis after 3 min, 6 min, and 12 min from a depth of 2 ft below the surface, and the sewage was then siphoned into the chlorine contact unit where it was mixed for approximately 2 min after

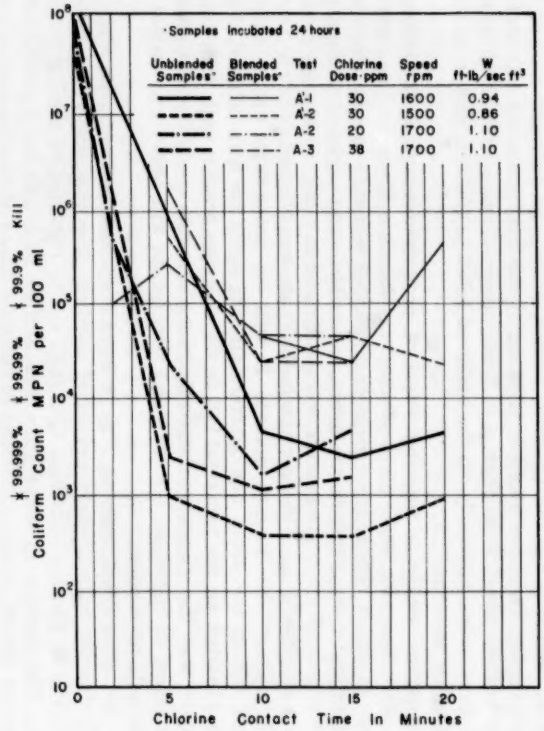
*Samples incubated 24 hours
Unblended Samples* | Blended Samples* | Test | Chlorine Dose ppm | Speed rpm | W ft-lb/sec ft³
A'-1 | 30 | 1600 | 0.94
A'-2 | 30 | 1500 | 0.86
A-2 | 20 | 1700 | 1.10
A-3 | 38 | 1700 | 1.10
Coliform Count MPN per 100 ml
† 99.999% † 99.99% † 99.9% Kill
Chlorine Contact Time In Minutes

FIG. 1.—COLIFORM KILLS ON COMMINUTED RAW SEWAGE

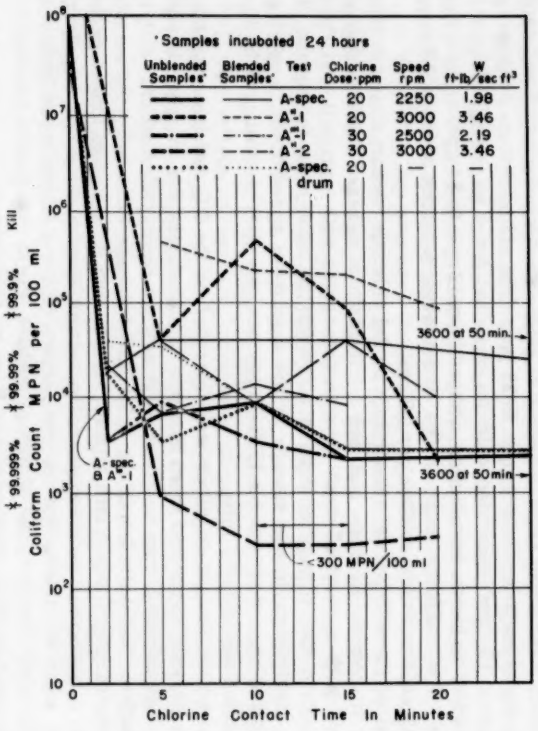
*Samples incubated 24 hours
Unblended Samples* | Blended Samples* | Test | Chlorine Dose ppm | Speed rpm | W ft-lb/sec ft³
A-spec. | 20 | 2250 | 1.98
A'-1 | 20 | 3000 | 3.46
A''-1 | 30 | 2500 | 2.19
A''-2 | 30 | 3000 | 3.46
A-spec. drum | 20 | — | —
3600 at 50 min.
A-spec. & A''-1
3600 at 50 min.
<300 MPN/100 ml
Coliform Count MPN per 100 ml
† 99.999% † 99.99% † 99.9% Kill
Chlorine Contact Time In Minutes

FIG. 2.—COLIFORM KILLS ON COMMINUTED RAW SEWAGE

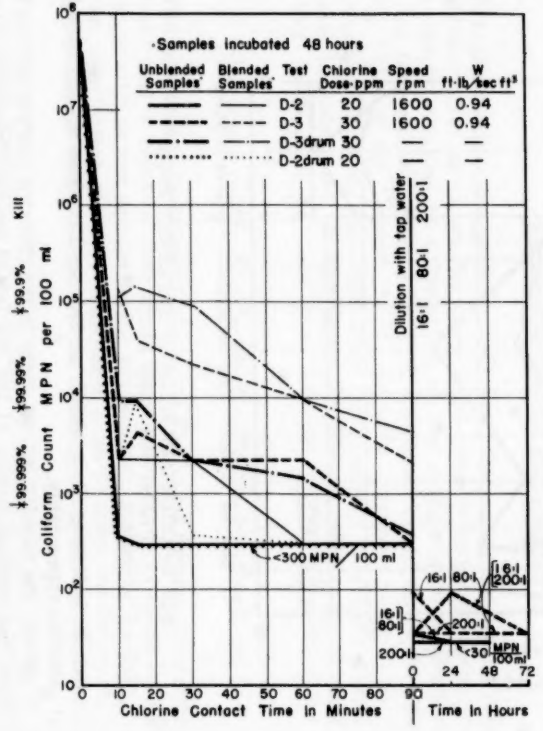

FIG. 3.—COLIFORM KILLS AND AFTER-GROWTHS ON COMMINUTED RAW SEWAGE

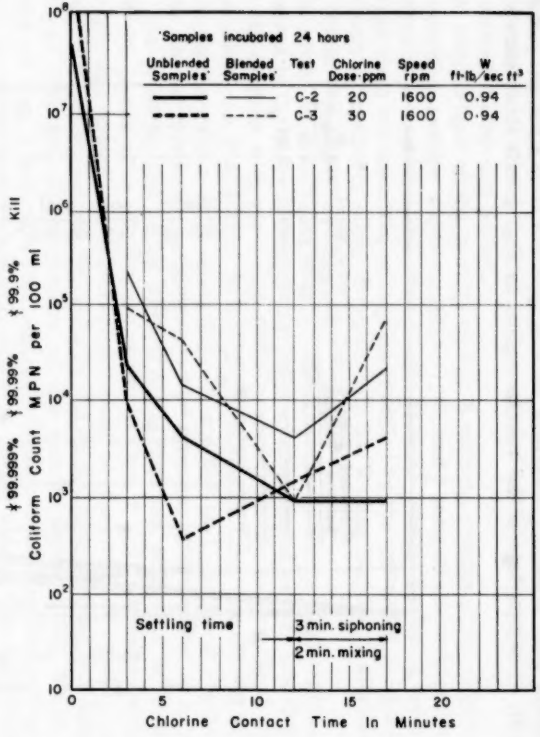

FIG. 4.—COLIFORM KILLS ON PARTIALLY SETTLED COMMINUTED SEWAGE

which samples were collected for further bacterial count. The samples collected from the drums after 6 min correspond approximately with a settling overflow rate of 3,600 gal per day per sq ft. Samples collected after 12 min correspond with a settling overflow rate of approximately 1,800 gal per day per sq ft. A comparison of the results shown in Fig. 4 with those shown in

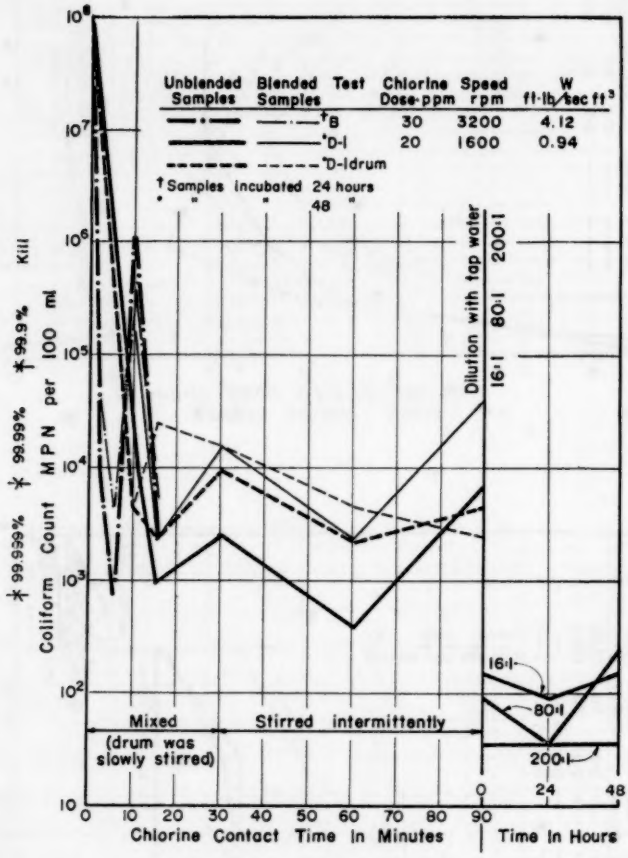

FIG. 5.—COLIFORM KILLS ON EFFLUENT FROM PLANT SETTLING BASIN

Figs. 1 and 2 indicates that short period settling does not improve the bacterial removal appreciably.

Fig. 5 shows the results of two runs in the chlorine contact unit on the effluent from the settling basins of the Nut Island Sewage Treatment Plant. The unchlorinated effluent was pumped into the chlorine contact unit, after which mixing was started and the chlorine added. Mixing was continued for

a 30-min contact period, after which the sewage was stirred intermittently throughout a total contact period of 90 min. Control samples of this sewage were pumped into drums for parallel chlorination and gentle stirring intermittently throughout the 90-min period. The results on Fig. 5 show the coliform counts on both blended and unblended portions of samples collected throughout the 90-min period.

A comparison of the results on Fig. 5 with the results of the chlorination of unsettled sewage shown on Figs. 1, 2, and 3 indicates no substantial improvement in bacterial kill after 10 min chlorine contact period of the settled sewage over the unsettled sewage as revealed by the unblended samples. The increase in coliform count obtained with the Waring blender is slightly less for the settled sewage than for unsettled sewage.

In order to determine whether aftergrowths of coliform bacteria may be expected in the river following discharge of chlorinated sewage into the river and its dilution with river water, the sewage from one run on Fig. 5 and two runs shown on Fig. 3 after 90 min chlorine contact time was diluted with tap water in the ratios of 16-to-1, 80-to-1, and 200-to-1. Coliform counts were made on the dilutions immediately after dilution, at the end of 24 hr and at the end of 48 hr and in the case of one of the runs, at the end of 72 hr. The coliform counts after dilution are shown on Figs. 3 and 5. These experiments indicate that no appreciable aftergrowths may be expected. The coliform counts on all of the dilutions was 240 and less and on all but 3 samples was less than 100 per 100 ml. A comparison of the results shown on Fig. 3 with those shown on Fig. 5 indicates that post-chlorination of well-settled sewage produces no better bacterial results in the receiving waters than does chlorination of comminuted raw sewage.

PRE-CHLORINATION EXPERIMENTS

Pre-chlorination in a primary treatment plant, using the settling tanks for chlorine contact, does, on the other hand, produce better bacterial removal than can be obtained by chlorination of raw sewage or post-chlorination of settling tank effluents. Tests by T. A. La Cava,[6] et al., of the performance, during 1953, of the Laconia, N. H., primary treatment plant, in which pre-chlorination is used, show that when the combined chlorine residual of the effluent is maintained above 1 ppm, the coliform count in the effluent of the settling tanks will be less than 240 per 100 ml about 98% of the time.

CHLORINE DOSES IN RAW SEWAGE FOR COLIFORM KILLS

The previously described tests at the Nut Island Sewage Treatment Plant indicate that a chlorine dose of 20 ppm to 30 ppm is required for effective coliform kills in raw sewage during dry weather. Studies by La Cava,[7] et al., on the chlorination of raw sewage taken from Laconia and Derry, N. H. with coliform counts ranging from 10 to 72 million per 100 ml showed that with

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[6] "Bacterial Reductions in the Chlorination of Sewage," by Thomas A. La Cava, et al., Report No. 2, New Hampshire Water Pollution Comm., February, 1955.

[7] "Bacterial Reductions in the Chlorination of Sewage," by Thomas A. La Cava, et al., Report No. 3, New Hampshire Water Pollution Comm., March, 1960.

gentle stirring and 15 min chlorine contact time the resulting coliform counts were not appreciably lower with chlorine doses above 20 ppm up to 170 ppm. They showed that 75%, or more, of all of the tests at chlorine doses of 20 ppm up to an including 160 ppm resulted in residual coliform counts equal to or less than 1,000 per 100 ml. Current (1960) studies by J. A. McCarthy,[8] et al., on the chlorination of raw sewage from Lawrence, Mass., show that with the dry weather sewage gently stirred for contact periods up to 30 min, at least 15 ppm to 20 ppm of chlorine is required for effective kill of coliform and that increased dosages up to 50 ppm do not result in much improvement (Tables 1 and 2). The results shown on Table 1 indicate, however, that a dose of 50 ppm may be necessary to maintain a combined chlorine residual of 10 ppm required for virus inactivation as shown hereinafter.

EFFECT OF VIOLENCE OF MIXING

In order to determine the feasibility of increasing the rate of coliform kill by more violent mix, the model chlorine contact chamber used in the Nut Island studies was equipped with a more efficient propeller. At the maximum speed of about 5,000 rpm, the velocity in the 2-in.-diameter tube is about 11 fps, the discharge is about 0.24 cfs, the turnover period is about 33 sec and the power dissipation is about 7.5 ft-lb per cu ft of tank. The mean velocity gradient corresponding to this power dissipation is about 530 fps per ft at 50°F. This approaches the maximum practical mean velocity gradient for a full scale chlorine contact chamber, because, for a 10 ft cubical tank the corresponding tube velocity is about 19 fps and the water horsepower is about 13.6 hp, and for a 16 ft cubical tank the tube velocity is about 22 fps and the water horsepower is 56 hp.

Runs by McCarthy,[8] et al., on Lawrence raw sewage in the model chlorine contact chamber with the new propeller, showed no improvement in the results with increased agitation. A run at the maximum speed of 5,000 rpm on sewage containing 160 million coliforms per 100 ml with a chlorine dose of about 39 ppm reduced the MF (membrane filter) count to 10 million (MPN by tubes 1.1 million) in 2 min, the MF count to 120,000 (MPN < 36,000) in 5 min, and the MF count to 10,000 (MPN = 3,600) at 10 min and at 20 min. These results are about the same as shown on Figs. 2 and 3 for gently stirred sewage.

La Cava,[7] et al., in their studies of chlorination of raw sewage from Concord and Derry, N. H., mixed in a Waring blender at various speeds less than 10,000 rpm, showed that very high power absorption is required for increased coliform kills. It was "found that the lowest combined level of chlorine contact and agitation time and power required to achieve estimated true densities of coliform bacteria equal to or less than 240 per 100 ml for nearly 100 per cent of the time under the conditions of the test are respectively: 30 ppm chlorine, 15-minutes contact time at 3,500 rpm in a Waring blender at a power absorption level (as a measure of turbulence) of 9.08 ft lbs per second (or 0.0165 horsepower)." Since 500 ml samples were used in these tests, the

[8] "Study on Chlorination of Raw Sewage," by Joseph A. McCarthy, unpublished work in progress at the Lawrence Experiment Sta. by Massachusetts Health Research Inst., Inc., under the sponsorship of the New England Interstate Water Pollution Control Comm.

TABLE 1.—TESTS BY McCARTHY ON CHLORINATION OF RAW SEWAGE[a]

Beaker No. (1)	ppm Cl_2 added (2)	Contact time, minutes 0 (3)	5 (4)	10 (5)	15 (6)	30 (7)
		Sheen colonies/100 ml T = 35 ± 0.5°C.			Membrane Filter 20 ± 2 hrs	
B-1	0	64,000,000	50,000,000	49,000,000	48,000,000	76,000,000
B-2	10	--	900,000	70,000	--	32,000
B-3	20	--	12,000	17,000	18,000	16,000
B-4	30	--	12,000	11,000	10,000	16,000
B-5	40	--	67,000	7,000	10,000	13,000
B-6	50	--	9,000	8,000	8,900	8,900
Count for a kill of 99.9% = 48,000						
		Combined chlorine residual, ppm				
B-1	0	0	0	0	0	0
B-2	10	-	0	0	0	0
B-3	20	-	1.80	2.42	2.21	0.94
B-4	30	-	5.32	4.90	4.90	4.50
B-5	40	-	8.24	7.42	7.83	6.57
B-6	50	-	11.8	11.2	11.2	10.5

[a] Free NH_3 = 38 ppm
Alb. NH_3 = 7.4 ppm
Temp. = 23.8°C. at start and 25.2°C. at end
July 13, 1960

TABLE 2.—TESTS BY McCARTHY ON CHLORINATION OF RAW SEWAGE[a]

Beaker No. (1)	ppm Cl_2 added (2)	Contact time, minutes 0 (3)	5 (4)	10 (5)	15 (6)	30 (7)
		Sheen colonies/ml T = 35 ± 0.5°C.			Membrane Filter 20 ± 2 hrs.	
B-1	0	77,000,000	100,000,000	57,000,000	103,000,000	108,000,000
B-2	10	--	300,000	137,000	46,000	40,000
B-3	15	--	15,000	23,000	19,000	18,000
B-4	20	--	75,000	27,000	13,000	23,000
B-5	25	--	7,100	10,600	9,200	13,000
B-6	30	--	5,200	6,700	9,700	13,600
Count for a kill of 99.9% = 57,000						
		Combined chlorine residual, ppm				
B-1	0	0	0	0	0	0
B-2	10	-	1.06	1.28	0.84	1.80
B-3	15	-	2.78	1.93	2.36	1.71
B-4	20	-	4.76	4.08	3.88	3.66
B-5	25	-	6.73	5.65	5.65	4.76
B-6	30	-	6.94	6.73	6.30	5.85

[a] Free NH_3 = 38 ppm
Alb. NH_3 = 10 ppm
Temp. = 23.4°C.
July 15, 1960

corresponding power absorption per cu ft is 514 ft lbs per sec and for a 10 ft cubical tank is 935 hp. It may be concluded, therefore, that agitation to increase the coliform kill is not practical, and that no agitation is needed except to mix the chlorine thoroughly with the sewage.

QUANTITY OF STORM WATER

McKee,[2] Palmer,[3] and Johnson,[4] as a result of three separate independent studies, have shown that the average dry weather flow of sanitary sewage is approximately equal to the discharge rate of the runoff from a rainfall having an intensity of 0.01 in. per hr. They have also shown that a rainfall of 0.02 in. to 0.03 in. is required to wet the surface of the ground so as to produce runoff into the storm drains or combined sewers. If the interceptors are designed for the peak dry weather flow (2 to 3 times the average dry weather flow), overflows of mixed sewage and storm water will occur, therefore, with rainfall intensities exceeding 0.02 in. per hr to 0.03 in. per hr after the ground is wet. The rate of flow of mixed sewage and storm water which must be chlorinated at any time is therefore approximately equal to 100 times the rainfall intensity in inches per hour times the dry weather flow up to a limit which is the capacity of the combined sewer. For example, if the average dry weather flow is 1 mgd and the rainfall intensity is 2 in. per hr for a sufficient duration to establish runoff from the entire area, the rate of flow that must be chlorinated is 200 mgd provided, of course, the combined sewer has this capacity. As will be shown later, the rate of chlorine application required for this example will be very much less than 200 times the rate of application during dry weather.

Studies were made by W. A. Healy, R. A. Eckloff,[9] et al., during 1959 of the hourly rainfall records for Concord, covering the summer period from June 16 through September 15, inclusive for the 10-yr period 1949 through 1958. The cumulative hourly precipitation was recorded and plotted for each of the 191 storms that occurred during these ten summers. All of these storms produced runoff and all of them would have produced overflows from interceptors designed for three times the average dry weather flow. The average frequency is 6.4 times per month. The total rainfall averaged 3.03 in. per month and the average rainfall that produced runoff after wetting was estimated at 2.83 in. per month, or about 93% of the rainfall.

The average dry weather flow of sanitary sewage at its equivalent of 0.01 in. per hr of rainfall (from the studies of McKee,[2] Palmer,[3] and Johnson[4] is equivalent to 7.20 in. per month (0.01 in. x 24 hr x 30 days) Thus, the total amount of storm water to be chlorinated at Concord is only about 40% (2.83/7.20) of the total amount of sanitary sewage to be chlorinated. The additional chlorine required to chlorinate the storm water would, therefore, not be great, even if the same chlorine doses were used for mixed sewage and storm water as are required for the dry weather sewage flow. It will be shown later that the chlorine concentration in the doses may be substantially reduced with increasing dilution of sewage with storm water.

An analysis of the Concord rainfall records indicates that, with combined sewers of adequate capacity and with interceptors designed for about three

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[9] "Treatment of Overflows from Combined Sewerage Systems," by Wm. A. Healy and R. A. Eckloff, et al., Staff Report No. 40, New Hampshire Water Pollution Comm., March, 1959.

times the average dry weather flow, about 21% of the rainfall will produce runoff which will be carried to the treatment plant without overflows and the remaining 79% will cause overflows from the interceptors.

CHLORINE RESIDUALS FOR VIRUS INACTIVATION

Studies have been made by S. Kelly and W. W. Sanderson[10] on the effect of chlorine in water on enteric viruses. Seven different strains of viruses were studied including five strains of polio and two strains of Coxsackie. These studies show, in general, that at pH values of 6 to 8 a concentration of 0.3 ppm of free residual chlorine for a contact period of at least 30 min is required for 99.9% or greater inactivation of enteric viruses. Studies by the same authors[11] on the effect of combined residual chlorine on polio and Coxsackie viruses indicate that about 10 ppm of combined residual chlorine with a contact period of about 1 hr is required for 99.7% or greater inactivation of enteric viruses. It is apparent from these studies that if chlorine contact chambers are provided for a 10-min contact at the capacity of the combined sewers (assuming reasonably adequate capacity) and that if a chlorine dose of about 10 ppm in excess of the chlorine demand after 1 hr is used for flows up to about 5 to 10 times the average dry weather flow, there will be sufficient contact time and sufficient combined chlorine residual to inactivate the viruses at these low flows. At the high flows the dose must be sufficient to produce a free chlorine residual so as to effect a more rapid kill of the viruses. If 0.3 ppm of free residual chlorine requires 30 min contact time, it is conceivable that about 1 ppm of free residual chlorine will be adequate for 10 min contact time, although there are no data at present to confirm this assumption. For combined sewers with capacities of less than about ten times the average dry weather flow, a 1-hr contact period should be provided for the flow capacity of the sewers.

BATCH EXPERIMENTS AT LAWRENCE

In order to explore the required chlorine doses for sewage mixed with storm water, experiments were undertaken at the request of the writer by McCarthy,[8] et al. at the Lawrence Experiment Station of the Massachusetts Department of Public Health. These experiments were undertaken during the summer of 1960 and were still in progress at the time this paper was written. The studies were directed by the Massachusetts Health Research Institute, Inc., under the sponsorship of the New England Interstate Water Pollution Control Commission. Sewage from the City of Lawrence was used in the experiments and Lawrence tap water was used in lieu of storm water.

Lawrence tap water was used as a substitute for storm water because of the obvious difficulty of collecting representative samples of storm water and because the tap water was free of coliform bacteria. Runs were made

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10 "The Effect of Chlorine in Water on Enteric Viruses," by Sally Kelly and W. W. Sanderson, American Journal of Public Health, October, 1958, p. 1323.

11 "The Effect of Combined Chlorine in Water on Poliomyelitis and Coxsackie Viruses," by Sally Kelly and W. W. Sanderson, American Journal of Public Health, January, 1960, p. 14.

with dilutions of tap water to sewage of 10-, 25-, 50-, and 100-to-1. The chlorine doses used in these runs was such as to produce a free chlorine residual of 1 ppm after 20 min contact time. Tests were made on each mixture to determine the "combined chlorine demand," which is defined herein as the chlorine dose required to yield a free chlorine residual of less than 0.05 ppm after 20 min contact time. The actual dose used in each case was 1 part per million in excess of the combined chlorine demand.

The question will be raised as to whether Lawrence tap water is a satisfactory substitute for storm water. The chlorine dose used for the higher dilutions (25 to 100 fold) is probably of the same order of magnitude as the dose that would be required for storm water because of the combined chlorine demand of the relatively high free ammonia content of the Lawrence tap water.

Palmer[3] presents evidence of excessive pollution of storm water runoff from analyses of street gutter water in the business district of Detroit during

TABLE 3.—ANALYSES OF STREET GUTTER WATER AT DETROIT DURING RAIN ON MARCH 22, 1949

Sample (1)	Time (2)	MPN (3)	T.S. ppm (4)	VS ppm (5)	5-day BOD ppm (6)	Airport Rainfall inches (7)
	AM					0.02 7 to 8 AM
1	8:55	930,000	660	299	234	
2	9:05	430,000	715	331		0.01 8 to 9 AM
3	9:15	430,000	726	340	124	
4	9:30	930,000	462	194		
5	9:45	430,000	914	414	132	
6	10:00	230,000	430	202		0.03 9 to 10 AM
7	11:25	43,000	714	370	96	0.02 10 to 11 AM
8	11:32	25,000	310	136		0.0
						0.08 total

a rain on March 22, 1949, as shown in Table 3. It will be noted that the volatile solids during the 2-1/2 hr period when samples were collected ranged from 136 ppm to 414 ppm and the 5-day BOD ranged from 96 ppm to 234 ppm. The coliform MPN for the first hour ranged from nearly 1 million down to about 230,000 per 100 ml. The writer has added the last column in Table 3 which shows the rainfall at the Detroit Airport during the period of sampling. It will be noted that the total rainfall was 0.08 in. and that the greatest rainfall during any 1 hr was 0.03 in., about three times the average dry weather flow. The actual rainfall on the area tributary to the point of sampling is not known; however, if the rainfall at the airport is any indication of the intensity it may be concluded that low rainfall intensity is the primary reason for the gross pollution of the samples collected. The coliform count is nevertheless only about 1% of what might be expected in normal sewage and is probably the result of droppings by birds and animals on the streets and roofs.

The tests by McCarthy[8] on the diluted sewage at Lawrence were made in beakers, gently stirred during the contact period. Coliform counts were made by means of the membrane filter technique (MF) with occasional checks

by tubes. The Lawrence Experiment Station has adopted the membrane filter technique for rivers and sewages in preference to the multitube technique because the results are more reproducible. Counts were made on unblended samples collected after various contact periods, and in most of the runs counts were also made after blending for two minutes in a Waring blender. The results of these tests are shown in Tables 4 to 9 inclusive.

Table 4 shows the results of a run with a 10-to1 dilution. It will be noted that the chlorine dose to produce about 1 ppm free chlorine residual was only 8.5 ppm. The coliform count in both unblended and blended samples was less than 100,000 in all contact periods up to and including 80 min.

TABLE 4.—TESTS BY McCARTHY ON CHLORINATION OF RAW SEWAGE DILUTED WITH LAWRENCE, MASSACHUSETTS, TAP WATER, 10% SEWAGE[a]

	Control	Chlorinated Samples		Amperometric Chlorine Residuals	
Contact Time, minutes	No Chlorine added Sheen colonies per 100 ml	Unblended Sheen Colonies per 100 ml	Blended Sheen colonies per 100 ml	Free ppm	Total ppm
(1)	(2)	(3)	(4)	(5)	(6)
0	57,000,000	--	--	--	--
10	73,000,000	< 100	16,000	1.25	6.0
20	65,000,000	< 100	10,000	1.05	6.0
40	84,000,000	40,000	44,000	1.0	5.6
80	66,000,000	55,000	63,000	0.95	4.4
1200	--	73,000	<1,000,000	0.4	3.6

	Chemical Analysis, ppm		
	Free NH_3-N	Albuminoid N	Chloride
Undiluted sewage	60	11	-
Diluted sewage	6.2	1.1	-
Tap water	-	-	-

[a] Combined chlorine demand, diluted sewage = 7.5 ppm
Chlorine added, diluted sewage = 8.5 ppm
Coliform sheen colonies, undiluted sewage = 380 million per 100 ml

Table 5 shows the results of a run with the dilution of 25-to-1. The chlorine dose in this case was only 2.3 ppm. Here again the coliform count in both unblended and blended samples was less than 100,000 for all contact periods from 10 min to 80 min inclusive.

Tables 6 and 7 give the results of two runs on sewage diluted 50-to-1 with Lawrence tap water. The chlorine dose in the first case was 1.6 ppm and in the second case was 1.65 ppm. In the first run (Table 6), the coliform count after 10 min was 300,000 but was reduced to 25,000 in 20 min and to 300 in 40 min. In the second case (Table 7), the coliform count for both blended and unblended samples was less than 100,000 after 10 min and was further reduced after 20 min and 40 min.

Tables 8 and 9 show the results of two runs by McCarthy on sewage diluted by 100-to-1. The chlorine dose in the first run (Table 8) was 1.3 ppm and in

TABLE 5.—TESTS BY McCARTHY ON CHLORINATION OF RAW SEWAGE DILUTED WITH LAWRENCE, MASSACHUSETTS, TAP WATER, 4% SEWAGE[a]

Contact Time min.	Control	Chlorinated Samples		Amperometric Chlorine Residuals	
	No. chlorine added Sheen colonies per 100 ml	Unblended Sheen colonies per 100 ml	Blended Sheen colonies per 100 ml	Free ppm	Total ppm
(1)	(2)	(3)	(4)	(5)	(6)
0	--	--	--	--	--
5	13,000,000	180,000	260,000	1.15	1.25
10	--	2,100	3,000	1.2	1.03
20	--	1,000	11,000	1.15	1.03
40	18,000,000	100	2,000	1.0	0.83
80	15,000,000	61,000	89,000	0.5	0.63

	Chemical Analysis, ppm		
	Free NH_3 -N	Albuminoid N	Chloride
Undiluted sewage	54	11	--
Diluted sewage	2.8	1.2	--
Tap Water	0.6	1.6	--

[a] Combined chlorine demand, diluted sewage = 1.3 ppm
Chlorine added, diluted sewage = 2.3 ppm
Coliform sheen colonies, undiluted sewage = 220 million per 100 ml

TABLE 6.—TESTS BY McCARTHY ON CHLORINATION OF RAW SEWAGE DILUTED WITH LAWRENCE, MASSACHUSETTS, TAP WATER, 2% SEWAGE[a]

Contact Time min.	Control	Chlorinated Samples		Amperometric Chlorine Residuals	
	No chlorine added Sheen colonies per 100 ml	Unblended Sheen colonies per 100 ml	Blended Sheen colonies per 100 ml	Free ppm	Total ppm
(1)	(2)	(3)	(4)	(5)	(6)
0	7,600,000	--			
2	4,700,000	3,200,000	--	1.50	1.66
5	7,900,000	1,060,000	--	1.35	1.66
10	6,500,000	300,000	--	1.25	1.66
20	13,700,000	25,000	--	1.05	1.66
40	10,000,000	300	--	1.05	1.66

	Chemical Analysis, ppm		
	Free NH_3 -N	Albuminoid N	Chloride
Undiluted sewage	60	10	47
Diluted Sewage, 1:50	3.6	0.8	12
Tap Water	-	-	12

[a] Combined chlorine demand, diluted sewage = 0.6 ppm
Chlorine Added, diluted sewage = 1.6 ppm
Coliform sheen colonies, undiluted sewage = 200 million per 100 ml

TABLE 7.—TESTS BY McCARTHY ON CHLORINATION OF RAW SEWAGE DILUTED WITH LAWRENCE, MASSACHUSETTS, TAP WATER 2% SEWAGE[a]

Contact Time min.	Control	Chlorinated Samples		Amperometric Chlorine Residuals	
	No chlorine added Sheen colonies per 100 ml	Unblended Sheen colonies per 100 ml	Blended Sheen colonies per 100 ml	Free ppm	Total ppm
(1)	(2)	(3)	(4)	(5)	(6)
0	1,200,000	--	--		
2	1,200,000	1,300,000	760,000	1.05	1.26
5	2,400,000	300,000	610,000	1.10	1.66
10	1,700,000	20,000	90,000	1.05	1.66
20	2,200,000	4,500	4,700	1.0	1.66
40	1,600,000	700	3,500	1.0	1.26

	Chemical Analysis, ppm		
	Free NH_3 -N	Albuminoid N	Chloride
Undiluted sewage	67	7.4	46.5
Diluted sewage	2.8	2.6	13
Tap Water	1.0	1.6	12

[a] Combined chlorine demand, diluted sewage = 0.65 ppm
Chlorine added, diluted sewage = 1.65 ppm
Coliform sheen colonies undiluted sewage = 220 million per 100 ml

TABLE 8.—TESTS BY McCARTHY ON CHLORINATION OF RAW SEWAGE DILUTED WITH LAWRENCE, MASSACHUSETTS, TAP WATER, 1% SEWAGE[a]

Contact Time Min.	Control	Chlorinated Samples		Amperometric Chlorine Residuals	
	No chlorine added Sheen colonies per 100 ml	Unblended Sheen colonies per 100 ml	Blended Sheen colonies per 100 ml	Free ppm	Total ppm
(1)	(2)	(3)	(4)	(5)	(6)
0	870,000	--	--		
2	--	--	--	0.90	--
5	--	147,000	--	1.20	--
10	--	43,000	22,000	1.00	--
20	--	1,800	5,800	1.20	--
40	--	2,300	2,500	0.70	--

	Chemical Analysis, ppm		
	Free NH_3-N	Albuminoid N	Chloride
Undiluted sewage	6.2	33	51
Diluted sewage	2.2	10	14
Tap Water	-	-	-

[a] Combined chlorine demand, diluted sewage = 0.3 ppm
Chlorine added, diluted sewage = 1.3 ppm
Coliform sheen colonies, undiluted sewage = 300 million per 100 ml

the second run (Table 9) was 1.6 ppm. The count on both blended and unblended samples was less than 100,000 after 10 min and was less than 3,000 after 40 min.

The batch tests by McCarthy, the results of which are shown on Tables 4 to 9, tend to indicate that good coliform kills can be had with mixtures of sewage and storm water, using chlorine doses very much less than are required with normal municipal sewage. The tests indicate that a chlorine dose of less than 2 ppm may be adequate with dilutions in excess of 50-to-1. Since Lawrence tap water was used as a substitute for storm water in these

TABLE 9.—TESTS BY McCARTHY ON CHLORINATION OF RAW SEWAGE DILUTED WITH LAWRENCE, MASSACHUSETTS, TAP WATER, 1% SEWAGE[a]

Contact Time min.	Control	Chlorinated Samples		Amperometric Chlorine Residuals	
	No chlorine added Sheen colonies per 100 ml	Unblended Sheen colonies per 100 ml	Blended Sheen colonies per 100 ml	Free ppm	Total ppm
(1)	(2)	(3)	(4)	(5)	(6)
0	980,000	--	--		
2	--	120,000	830,000	1.25	1.66
5	--	80,000	120,000	1.18	1.66
10	--	700	2,000	1.20	2.05
20	--	200	0	1.20	1.66
40	--	1,000	200	1.20	1.66

	Chemical Analysis, ppm		
	Free NH_3-N	Albuminoid N	Chloride
Undiluted sewage	74	9.8	44
Diluted sewage	1.6	1.2	12
Tap Water	-	-	-

[a] Combined chlorine demand, diluted sewage = 0.6 ppm
Chlorine added, diluted sewage = 1.6 ppm
Coliform sheen colonies, undiluted sewage = 300 million per 100 ml.

experiments, it is most desirable to confirm these conclusions by means of plant scale tests using actual storm water.

CONTINUOUS FLOW CONTACT CHAMBERS

In order to throw some light on the effect of short circuiting on coliform kills in continuous flow contacts chambers, McCarthy,[8] et al., made several runs on a continuous flow channel divided into three compartments by means of baffles. Mixtures of sewage and tap water were regulated to flow continuously through the chamber at pre-determined rates. Chlorine was added in a small compartment just prior to the entrance to the chamber where it was violently mixed with the sewage mixture.

Prior to the runs with the continuous flow channel, chlorine tests were made with slugs of chlorine that indicated that the flow pattern was not

such as to minimize short circuiting. The first chlorine appeared at the effluent in about 30% of the detention period and the peak concentration appeared in about 50% of the detention period. During the runs with chlorine, samples of the effluent were taken for coliform determinations after an elapsed time from the start of each run equal to about twice the detention period.

One run was made with a 50-to-1 dilution of Lawrence tap water to sewage and a 10-min contact period. The chlorine dose was 1.7 ppm and the free chlorine residual after 10 min was 1.1 ppm. The chloiofm counts indicated practically no coliform kill in the chamber during this run.

A second run was made with 100-to-1 dilution of the sewage and a chlorine contact period of 10 min. In this case the dose was 1.5 ppm and the free chlorine residual after 10 min was 0.35 ppm. A very substantial reduction in coliform count was obtained in this run with an MF count in the effluent of 1,100 unblended and 3,000 blended.

Two additional runs were made with 100-to-1 dilution but with 20 min contact in both cases. The free chlorine residual after 20 min was 0.38 ppm in one case and 1 ppm in the other. In one of the runs the MF count in the effluent was 500 unblended and 14,000 blended and in the other run the MF count was 200 unblended and 1,500 blended.

Two runs were made with 25-to-1 dilution, one with a 10-min contact period and the other with a 20-min contact period. The free chlorine residual was 0.4 ppm for the 10-min contact period and 0.43 ppm for the 20-min contact period. The MF count for the 10-min contact period was 360,000 unblended and 2.3 million blended. The MF count in the effluent after the 20-min contact period was 30,000 unblended and 52,000 blended.

One run was made with a 10-to-1 dilution and a 20-min contact period. The free chlorine residual after 20 min was 1.1 ppm with a dose of 9.5 ppm. The MF coliform count in the effluent was 1,200 unblended and 28,000 blended.

These runs with continuous flow indicate the necessity of minimizing short circuiting in the chlorine contact chamber by providing as many compartments in series as is feasible and the necessity of keeping a substantial chlorine residual in the contents of the tank between rainstorms so that the incoming mixed sewage and storm water at the beginning of a storm will not be inadequately chlorinated when it mixes with the tank contents. This may be accomplished by recirculating the chamber contents by pumping and chlorinating the recirculated mixed sewage and storm water so as to keep the chlorine residual high. For example, with a dry weather flow of 1 mgd and a combined sewer capacity for a rainfall of 2 in. per hr or 200 mgd, the volume of the chlorine contact chamber for a 10-min contact time at peak flow is 1.4 mg. If the chamber contents are circulated during dry weather at 2 mgd, the turnover period will be about 17 hr. A chlorine dose of about 1 ppm in the recirculated flow should be adequate to keep the residual at any desired level. This is equivalent to 2 ppm at the dry weather flow, which is a very small part of the chlorine requirement for the dry weather flow.

CHLORINE REQUIREMENTS

The previously described experiments by McCarthy[8] indicate required chlorine doses for mixed sewage and storm water substantially as shown in Table 10. The chlorine doses shown in Table 10 are those that were used in the experiments. Under each of these doses is shown an equivalent dose at the

dry weather flow that was obtained by multiplying the actual dose by the dilution ratio. These equivalent doses may be compared with the expected dose of 25 ppm to 30 ppm for the dry weather flow in order to indicate the probable rate of chlorine application. The highest equivalent dose is at the 100-to-1 dilution, which is at some 5.5 to 6.5 times the rate of application of chlorine during dry weather. It appears from this that a chlorination capacity of not more than about ten times the average required for the dry weather flow should be adequate for most installations. This is, of course, very much less than the 200-fold ratio of flows that may be expected from small areas served with adequate combined sewer capacity.

As indicated by the Concord studies the total amount of storm water runoff throughout the year that must be chlorinated is only about 40% of the dry weather flow of the sewage. Since the required chlorine dose in ppm decreases substantially with increased dilution of the sewage, it is probable that the increased amount of chlorine required annually for the storm water will not exceed about 10% of the chlorine required for the dry weather flow. To this must be added another 10%, more or less, to maintain a high chlorine residual in the recirculated contents of the chlorine contact chamber between rainstorms.

TABLE 10.–INDICATED CHLORINE DOSES FOR MIXED SEWAGE AND STORM WATER

Dilution of dry-weather flow	10	25	50	100
dose, ppm	8.5	2.3	1.6	1.3
equiv. dose at DWF, ppm	85	58	80	130
dose, ppm			1.65	1.3
equiv. dose at DWF, ppm			83	130
dose, ppm				1.6
equiv. dose at DWF, ppm				160

Thus, the total chlorine required for chlorinating the storm water and the dry weather flow of sanitary sewage is only about 20% greater than the chlorine requirement for the dry weather flow.

PRACTICAL APPLICATION

In order to explore the contact chamber water surface area requirements for various size tributary areas, computations have been made based on runoffs as shown in Table 11. These runoffs are relatively high and will correspond with rainstorms having a 10 to 15-yr frequency in the eastern United States. Table 11 presents the water surface area requirements for vertical wall tanks, for both 10 ft and 15 ft depths. In most cases it will probably be found that the capacity of the combined sewers is not equal to the runoffs shown in Table 11 and the contact chamber water surface area will be determined by the capacity of the main combined sewer.

The water surface areas shown in Table 11 have been plotted on Fig. 6 to indicate graphically the relation of contact tank surface area to the tributary area. It will be noted from Fig. 6 that a tributary area of 1 sq mile

(640 acres) will require approximately 1 acre of contact chamber water surface as a maximum. A tributary area of 10 sq miles will require approximately 5 acres of contact chamber water surface area.

In many cases it will be necessary to construct the contact chambers of reinforced concrete. It is believed, however, that where land is cheap and the location of the contact chamber is not in a congested area, the chamber may be constructed with unlined earth embankments.

For each installation it will be necessary to have a meter of some sort for measuring the flow of combined sewage and storm water which, in turn, will control the chlorine dose. It will probably also be necessary to have automatic control of the dose by means of chlorine residual meters. For effective results the chlorine must be mixed uniformly with the incoming flow, and during dry weather with the recirculated flow.

Two types of installations are anticipated, one to chlorinate only the overflows from interceptors and the other to chlorinate the total flow where the dry weather flow is not intercepted for other forms of treatment. In both types, mechanically cleaned bar racks should be provided for the full capacity of the main combined sewer to remove unsightly, large, suspended matter. Where the total flow is chlorinated, comminution should be provided following the racks with capacity sufficient for the dry weather flow.

TABLE 11.—MAXIMUM WATER SURFACE AREA REQUIRED IN CHLORINE CONTACT CHAMBERS FOR 10 MINUTES CONTACT

Tributary Area A, in Acres (1)	Run off Ci, in inches per hour (2)	Tank Surface Area, in square feet	
		For 10 ft depth (3)	For 15 ft depth (4)
10	2.5	1,500	1,000
100	2.0	12,000	80,000
500	1.5	45,000	30,000
1,000	1.25	75,000	50,000
10,000	0.5	300,000	200,000

It is anticipated that no odor nuisances will develop because the contact chambers will be kept full at all times and a high chlorine residual will be maintained in the chamber contents. The hydraulic characteristics of the chambers should be such as to discourage the accumulation of sludge and thus avoid sludge handling problems. In some cases gentle stirring of the chamber contents may be desirable to prevent accumulation of sludge. However, if sludge does accumulate it should cause no odor nuisance because of the high chlorine residual.

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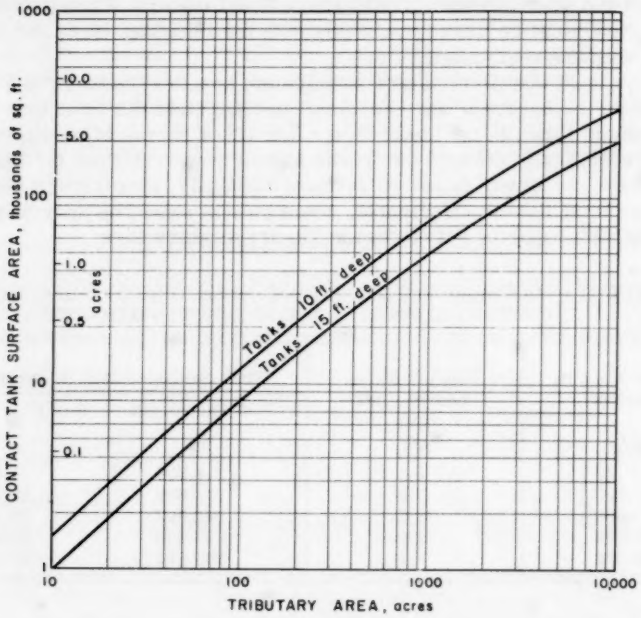

FIG. 6.—MAXIMUM WATER SURFACE AREA REQUIRED IN CHLORINE CONTACT CHAMBERS FOR 10 MINUTES CONTACT

the mixing equipment. We are indebted to the New England Interstate Water Pollution Control Commission, Mr. Joseph C. Knox, Executive Secretary, for the allocation of funds for the research work at the Lawrence Experiment Station, and to the Massachusetts Health Research Institute, Inc., which directed the work at the Lawrence Experiment Station. We are particularly indebted to Mr. Joseph A. McCarthy under whose immediate direction the experiments at Lawrence were undertaken. The author appreciates the help of his associate, Mr. Robert H. Culver, who has been directly involved in many of the studies and hias assisted in the preparation of this paper.

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MARINE DISPOSAL OF WASTES

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Committee on Sewerage and Sewage Treatment

INTRODUCTION

This report is a review of the literature dealing with the marine disposal of wastes.

The availability and appreciation of basic knowledge concerning marine disposal of wastes has increased rapidly during the past few years. In 1955, E. A. Pearson reviewed and evaluated both published and unpublished information (1).[1] The present review is concerned with subsequent work, particularly in regard to California waters.

The expanding interest in the subject has been evidenced not only by the literature, but by the number of symposia and conferences which have dealt with various features of marine disposal. These have included the 1958 seminar at Nice (2), the Second Seminar on Biological Problems in Waste Disposal at the Taft Engineering Center in Cincinnati, 1959 (3), the First International Conference on Waste Disposal in the Marine Environment at Berkeley, 1959 (4), and the Symposium on Oceanography and Related Estuarial Pollution Problems of the Northwest at Portland, 1959 (5).

Aspects of marine disposal of wastes may be grouped as follows: data collection and evaluation; bacteriology; biology; physical and chemical oceanography; estuaries and semi-enclosed bays; design and construction; and special studies and current research.

DATA COLLECTION AND EVALUATION

"The Oceans," of H. U. Sverdrup, M. W. Johnson, and R. H. Fleming (6) and P. S. Welch's "Limnological Methods," (7) provide general treatment of

Note.—Discussion open until June 1, 1961. Separate discussions should be submitted for the individual papers in this symposium. To extend the closing date one month, a written request must be filed with the Executive Secretary, ASCE. This paper is part of the copyrighted Journal of the Sanitary Engineering Division, Proceedings of the American Society of Civil Engineers, Vol. 87, No. SA 1, January, 1961.

[1] Numerals in parentheses, thus (1), refer to corresponding items in the Bibliography.

the instruments, techniques, and data analysis methods of oceanography and limnology, respectively. The Hydrographic Office has published (8) detailed instructions for the use of the more common types of equipment. J. D. Isaacs and C. O. Iselin, et al. (9); A. C. Vine (10), and R. C. Vetter, et al. (11), have reviewed recent advances in determination and evaluation of physical and chemical properties of ocean waters.

Water clarity has been measured for many years by observing the depth to which a Secchi disc, a white circle generally of 30 cm diam, can be seen by eye. More recently, various photometric techniques have been developed to measurement of light transmission characteristics of water. Modern methods for determination of light penetration have been discussed by S. Q. Duntley (12) and R. W. Holmes (13).

Chemical methods for the determination of major and minor constituents of sea water are outlined in detail by H. W. Harvey (14), the Allen Hancock Foundation (15), and H. Barnes (16).

Temperatures of near-shore waters are normally determined with standard laboratory thermometers in surface (bucket) samples and by the bathythermograph (8),(17) in subsurface waters to depths of 900 ft. The latter provides a continuous trace of temperature vs. depth on a smoked glass slide which is read by means of a calibrated grid. Where a high degree of precision is required in subsurface observations at predetermined points, reversing thermometers (6),(8) are used; these are not ordinarily required for surveys of waste-receiving waters.

There is a wide choice of equipment for sampling waters at depth, much of which is unnecessarily complicated. For most work in coastal receiving waters, the Frautschy bottle (18) is preferred because of its simplicity and low cost while the Nansen bottle (6),(8) is required only occasionally. The Zo Bell sampler (19) was developed for bacteriological work in very low bacterial populations and was designed to prevent contamination from any water above the point of sampling. Several of the various samplers may be operated simultaneously at different depths on a single wire by means of a series of weights or "messengers."

Comprehensive reviews of current measuring devices have been published by G. Böehnecke (20) and J. W. Johnson and R. L. Weigel (21). Techniques for reduction of current data which result in the identification of components have been discussed by the U. S. Coast and Geodetic Survey (22),(23), K. F. Bowden (24), H. Mandelbaum (25),(26), Johnson and Weigel (21), Weigel and Johnson (27), V. F. C. Veley (28), and the Interstate Sanitation Commission (29). Currents may be measured by the point (Euler) or the path (Lagrange) method. The data are analyzed to determine the effects of winds, tides and residual currents. Once the local effects of winds are known from hindcasting, meteorological records that usually extend over a comparatively long period form the basis for forecasting probable future currents. Occasionally, the observed currents vary markedly in both direction and velocity from that which would be expected from the wind and tide. There is no proven method for predicting the sort of extreme values that have been observed during waste disposal surveys by the Cities of Los Angeles (30) and San Diego (31) in California. Some preliminary work (unpublished) indicates that E. J. Gumbel's (32) method works reasonably well.

Currents in the open sea may be computed from the density distribution in much the same manner as that used by meteorologists working from barometric data. Sea-water density is a non-linear function of temperature and

salinity. The detailed procedures for computation of these (geostrophic) currents is given by Sverdrup, et al., (6). The tables of E. C. La Fond (33) and the Hydrographic Office (34) are of considerable assistance in such computations. It is sufficient here to note that in the northern hemisphere when facing in the direction of the current, the lighter (warmer and/or less saline) water lies on the righthand side.

The collection of biological data is discussed by Sverdrup, (6), Welch (7), the Hydrographic Office (8), and in "Standard Methods" (35). Additional general information is presented by J. W. Hedgepeth, et al., (36) and by Barnes (37). The significance of plankton determination is reviewed by J. B. Lackey (38). Various aspects of fish sampling are discussed by G. A. Rouncefell and W. H. Everhart (39), L. K. Boerema (40) and G. H. Allen, et al., (41). Techniques for sampling of bottom-dwelling organisms are presented by J. L. Barnard and G. F. Jones (42). The statistical methods of quality control using multidimensional surfaces of normal distribution have been successfully applied by T. W. Beak, et al., (43) in detecting pollution in Lake Ontario . . . "long before a trained observer would suspect that trouble was developing." Th. G. N. Dresscher (44) has used data-grouping methods in evaluating environmental changes in a community of microorganisms in the canal receiving effluent from the Amsterdam sewage treatment plant.

Samples of bottom sediments are often incidentally obtained during the course of biological sampling. The use of gravity or piston corers is preferred for sediment samples; descriptive and operating data may be found in the Hydrographic Office Instruction Manual (8) and in the Allan Hancock Foundation Manual (15). The latter reference and Barnes (16) present methods for the physical and chemical analysis of sediments.

Numerous tracer techniques have been used to mark the extent of fields from submarine outfalls. T. Braarud and E. Fǿyn (45) have studied nitrite distribution in receiving waters. The City of Los Angeles has used combinations of coliform bacteria density, salinity, ammonia-nitrogen, fluorescein, and radiotracer observations to outline treatment plant effluent fields and to study diffusion (46), (47). J. N. Putnam, et al., (48) have reported on the combined use of radioactive (phosphorus-32) and bacterial *(Serratia indica)* tracers. C. H. Lawrance (49) has prepared graphic solutions for simplifying dilution computations. Pearson has used Orzan, dried spend sulfite liquor solids, as a tracer (50). The use of the specific fluorescence of Rhodamine B has been described by J. H. Carpenter (51) and D. W. Pritchard (52). In general, surveys using radioisotopes or fluorescent techniques provide the most detailed information. A detection limit of from 2×10^{-11} to 4×10^{-12} is reported (52) for Rhodamine B.

The importance of navigation cannot be overemphasized. Earlier techniques are detailed in the U. S. Coast and Geodetic Survey's, "Hydrographic Manual" (53). Advances in electronic surveying methods have been discussed at a recent symposium (54).

There is an expanding choice of equipment and supplies to be used in sampling and testing. J. H. Ryther, et al., (55) have recently prepared a list of manufacturers of the various items.

BACTERIOLOGY

The sanitary bacteriology of waste disposal in marine waters has received more attention from engineers than all other aspects. Pearson (1) summarized

investigations of the persistence of enteric bacteria in sea water made from 1885 to 1955; these studies were made under variously controlled conditions.

Subsequent field studies have been made in coastal waters of southern California by the City of Los Angeles (30) and the University of Southern California (47) in connection with the expansion of the Hyperion Treatment Plant; this work has been summarized by C. G. Gunnerson (56). Y. Sekine, et al., (57),(58) have reported that the bacterial pollution extends over about one-half of Tokyo Bay. J. G. W. Bolomey (59) has presented the status of pollution of Netherlands beaches by water from the Rhine.

G. T. Orlob (60) described techniques for inoculation of samples so as to avoid refrigeration. Membrane filter and lactose fermentation techniques have been compared by M. W. Presnell, et al., (61), M. Levine, et al., (62) and W. L. Henderson (63). H. W. Jannash and G. E. Jones (64) reported that numbers of marine bacteria determined by two direct-count methods were always higher than those determined by culture methods because of aggregation, selective effects of media, and the presence of inactive cells.

Several statistical treatments of bacterial indices have been presented by C. J. Velz (65), H. A. Thomas, Jr. (66), R. Pomeroy (67), E. K. Harris (68), and R. L. Woodward (69).

Factors governing the persistence of enteric bacteria in sea water are reviewed and discussed by Pearson (1) and A. F. Carlucci and D. Pramer (70). Laboratory and controlled field experiments have shown that sedimentation, sunlight, starvation, bactericidal substances, microbial antagonism, bacteriophage, and predation affect bacterial survival.

Qualitatively, the importance of sedimentation is shown by problems in shellfish sanitation discussed by C. E. Zo Bell (19) and Pearson (1). Sekine, et al., (58) found high populations of enteric bacteria in bottom muds of Tokyo Bay. S. C. Rittenberg, et al., (71) discussed the significance of the large bacterial populations on the sea floor around marine outfalls in southern California.

J. K. Johannesson's (72) work indicates that the heat-labile bactericidal substance reported by many investigators is probably iodate. R. A. Barklay and T. G. Thompson (73) have found that normal iodate concentrations in seawater range from 28 to 59 g per l.

Evidence that plankton algae produce antibiotics was found by E. Steeman Nielsen (74) for the freshwater alga, *Chlorella pyrenoidosa*, and the marine diatom *Thalassiosira nana*.

The importance of bacteriophage is not established; some of the difficulties in making an evaluation of this factor are shown in the general review by J. S. K. Boyd (75).

The usual method of evaluating bacterial pollution of receiving waters is to make areal surveys at sampling stations located on a grid pattern or along radial lines. A knowledge of the average currents then makes it possible to make a qualitative estimate of the persistence of bacteria in the sea-water. A more precise evaluation requires periodic sampling from tagged masses of the sewage effluent-sea water mixture. The decline rate can then be expressed as the time in hours for a 90% reduction (T-90) in coliform or other enteric bacteria densities. This has been done at three southern California submarine outfalls where the T-90's for coliform bacteria in surface waters have been found to vary from 1.5 to 6.5 hr (30),(47),(56). The effect of dilution ($T\text{-}90_d$) depends on the location; the effect of mortality ($T\text{-}90_m$) including sunlight, starvation, bactericide, antagonism, phage, and predation appears to be

essentially constant; and the effect of sedimentation ($T\text{-}90_s$) varies with the character of the effluent (56). These are summarized in Table 1.

It may be noted that Bolomey's (59) data indicate a combined T-90 of about 7.8 hr for coliforms discharged by the Rhine into the North Sea.

Since sedimentation is always important and may be the predominant factor in reduction of coliforms in surface waters, it is appropriate to examine the fate of these coliforms which have settled to the bottom. Their persistence is relatively long with a probable T-90 of 1 to 10 months (56). The probability of resuspension of these coliforms has been discussed by Rittenberg (30) and Gunnerson (56); it is small.

The desirability of obtaining bacteriological indices of pollution in relatively short times has favored the development of the membrane filter methods (61),(62),(63) mentioned earlier. Levine, et al., (76) have described methods for the determination of coliform and *E. coli* indices in 24 hr to 30 hr.

The public-health significance of coliform densities has been discussed by W. F. Garber (77). He found that allowable bacterial concentrations in bathing waters which were presumably based on epidemiological experience varied by as much as an order of magnitude. More recently, B. Moore (78) and

TABLE 1.—TIME FOR 90% REDUCTION IN HOURS

Plant	Treatment	$T\text{-}90_d$	$T\text{-}90_m$	$T\text{-}90_s$	T-90 Combined
Hyperion	Secondary	20	17.8	21.0	6.5
Hyperion	Primary	20	17.8	5.3	3.4
Orange County	Primary	5 to 10[a]	17.8	2.0 to 2.4	1.5

[a] Estimated from Rittenberg's data (47).

Moore, et al., (79) have concluded that ocean pollution is an aesthetic problem rather than one of public health.

In a larger sense, the significance of the many varieties and great numbers of marine bacteria in the stabilization of waste products has not been evaluated. In this connection Zo Bell (19) has stated, "It is because bacteria are able to mineralize virtually all kinds of organic matter that the sea has aptly been characterized as the world's largest and most efficient septic tank." However, the principles of bacterial transformation of organic debris into dissolved mineral components in the ocean waters have been outlined by several investigators, notably G. A. Riley (80), Rittenberg, K. O. Emery, and W. L. Orr (81),(82); their general findings may be appropriately applied to the specific case of sewage disposal.

BIOLOGY

The biological effects of a waste-disposal system are reflected throughout the water column. The discharge may be expected to effect the floating or weakly swimming forms (plankton), strongly swimming forms as fish and squid (nekton), and attached, burrowing, or crawling forms (benthos).

It is reasonable to assume that the effects of dissolved substances will be most noticeable in the plankton and that settleable (in the ocean) solids will

have the greatest effect on the benthos. In municipal-sewage effluents, the suppressing action of certain components of the waste is opposed by the effect of nutrients in the discharge.

N. B. Hume, et al., (83) characterized the discharge from the City of Los Angeles in Santa Monica Bay. It has been estimated that about 15% of the flow is industrial waste. The daily discharge contains about 200 tons of suspended solids, 50 tons of nitrogen, 14 tons of phosphate-phosphorus, 22 tons of silica, 2 tons of various heavy metals, and some 8 lb to 10 lb of vitamin B_{12} activity.

O. Hartman (84) found in 1956 that the settled solids from Hyperion affected the benthos to a distance of about 6 miles. This is reflected in increased numbers of bottom fish (83),(85). R. E. Stevenson and J. R. Grady (86) observed significant increases in nutrients in surface waters of the bay; these are reflected in increased plankton populations, particularly dinoflagellates, copepods, and diatoms (83).

Hartman's (84) studies of the benthos were based primarily upon polychaetous annelid worms. D. J. Reish (87),(88),(89),(90), Reish, and Barnard (91) have found similar effects from other waste discharges, particularly in harbors. Barnard, Hartman, Jones (92), and Hartman (93) have examined the benthos along 250-miles of southern California to a depth of 50 fathoms in order to establish background conditions for comparison with existing and future areas of waste disposal. J. M. Resig (94),(95) has reported on benthic formanifera in the same area.

W. J. North and K. A. Clendenning have, in a series of reports (96),(97), reported on the effects of waste discharges on the giant kelp, *Macrocystis Pyrifera*. A major problem in the study has been to separate natural and man-made variations; this has required evaluation of historical changes in kelp beds (98). Clendenning has measured the toxicity of dilute solutions of copper, hexavalent chromium, chlorine, detergent, blooms of the dinoflagellate, *Gonyaulax polyedra*, phenol, chlorinated phenols, and fuel oil; he concludes that normal initial dilutions of municipal discharges preclude direct toxicity effects.

The relationship between nutrients and plankton in the sea is discussed by Sverdrup, et al., (6), Harvey (14), B. H. Ketchum (99), C. C. Davis (100), Johnson (101), and Barnes (102). As noted previously, the quantities of nutrients discharged with sewage effluents can be great.

The fertilizing effects of sewage discharges have also been studied in Biscayne Bay, Florida by F. G. W. Smith, et al., (103); in Oslo Fjord by O. Sundene (104) and Føyn (105); and in the Port of Marseilles by R. Gilet (106). Typically, this sort of fertilization results in eutrophication, that is, a great reduction in numbers of species with a simultaneous increase in numbers of individuals.

The recent studies of Davis (107) in Cleveland Harbor; W. T. Edmondson, et al., (108) in Lake Washington; and H. Curl, Jr. (109) in western Lake Erie show eutrophication in lakes which is similar in most respects to that in marine waters mentioned previously.

The metabolism and production of marine bays has been studied by H. T. Odum, C. M. Hoskin (110), K. Park, et al., (111), and Odum (112). It is shown that diurnal variations in dissolved oxygen, temperature, and pH computed as total CO_2 can form a basis for determining the natural purification capacity of the water.

Qualitative estimates of the effects of nutrients in sewage effluents can be made from operating data of some sewage treatment processes. W. J. Oswald

and H. B. Gotaas (113) found that 1 part by weight of nitrogen could produce 10 parts of algal-cell material in an experimental oxidation pond. The terminal fauna of a trickling filter are probably more representative of the fauna of many receiving waters. W. B. Cooke (114) has described the snails, worms, and insects found at the Dayton, Ohio plant. W. M. Ingram, et al., (115) reported that an average of 30 lb of snails *(Physa integra)* were produced per 1,000,000 gal, and that during spring blooms, the quantity increased to 50 lb per 1,000,000 gal. The snails form a significant part of the terminal weight. Even so, the value of 30 lb per mg corresponds to only about 1 part of animal weight to 7 parts of nitrogen in trickling-filter influent.

The evidence for greater production of marine plankton in the vicinity of sewage-effluent discharges is strong. It has been speculated that this may be extended to plankton blooms. No evidence for such an effect has been found. M. Brongersma-Sanders (116) has summarized the incidence of marine blooms throughout the world; the nutrients from runoff and coastal upwelling of mineralized waters from depths at which phytoplankton growth is small or absent because of the paucity of light (13) are reflected in the numbers of reported blooms in coastal waters generally. Blooms are also found in the open sea where the plankton utilized nutrients brought to the surface in areas where surface currents diverge. Richard Bainbridge (117) has noted patches of as much as 40 miles by 180 miles in area.

Commensalism, parasitism, and symbiosis in marine forms have been discussed by R. P. Dales (118), B. H. Hopkins (119), and C. M. Younge (120), respectively. The effects of waste discharges have not been evaluated in these respects.

Cancerous growths found on *Genyonemus lineatus* the white croaker, by F. E. Russell and P. Kutin (121) suggest that this bottom-feeding fish may be sensitive to some components of municipal waste discharges.

The value of indicator organisms in pollution studies is apparent from considerations discussed previously. The use of indicators in fresh waters is generally similar to that in marine waters; the status of such work was a subject at a 1956 USPHS seminar (122). Protozoa, algae, fungi, molluscs, insects, and fish have been studied by Lackey (123), C. M. Palmer (124), Cooke (125), Ingram (126), R. R. Gaufin (127), and P. Doudoroff (128), respectively.

Some of the organisms that abound in receiving waters may, under some circumstances, be classified weed species of which undesirable fish or nuisance blue-green algae are examples. Nevertheless, these organisms tend to return the receiving water quality to a natural state. A. C. Redfield (129) has shown that, in sea water, phytoplankton concentrate nitrogen and phosphorus by a factor of 10^5. Generally similar relationships may be expected in fresh waters. A number of investigators, beginning with C. N. Sawyer (130) in 1952, and including Karl Imhoff, Hon. M., ASCE (131), Lackey (132), and Føyn (133) have proposed the reduction of the plant nutrients, nitrogen and/or phosphorus, in sewage treatment so as to avoid eutrophication of receiving waters.

Since the isolation in 1948 of vitamin B_{12}, and the subsequent discovery by S. R. Hoover, et al., (134) of significant quantities of this vitamin in sewage sludge, a large amount of information has become available. H. Y. Neujahr's work (135), (136), (137) identifies eleven B_{12} factors which are produced during treatment processes. She has found that the B_{12} activity in digested sludge from activated sludge plants is primarily due (70% to 90%) to cyanocobalamin,

while activity from plants employing only anaerobic biological treatment is due about equally to cyanocobalamin and about half to other factors; and that thermophilic digestion destroys all B_{12} activity. The B_{12} is adsorbed onto the surfaces of solids and is discharged from the Hyperion Treatment Plant with both the plant effluent and digested sludge discharges.

The occurrence and ecological significance of vitamin B_{12} in marine waters is receiving increasing amounts of attention. S. H. Hutner, et al., (138), T. J. Starr, et al., (139), and K. W. Daisley (140),(141) have discussed and compared techniques for determining B_{12} activity.

Surface-sea-water samples from the North Atlantic have been found to contain 0.0002 μg per l of B_{12} in summer and 0.002 μg per l in winter by C. B. Cowey (142); phytoplankton contained 0.02 to 0.03 μg per gm wet weight and zooplankton contained 0.02 to 0.14 μg per gm. K. Kashiwada, et al., (143) found up to 0.002 μg per l in surface samples and up to 0.007 μg per l in depth samples from the North Pacific. Daisley and L. R. Fisher (144) found averages of 0.0006 μg per l between the surface and 100 m, and 0.0023 μg per l between 100 m and 3,600 m during the early summer in the north Atlantic. Kashiwada, et al., (145) found maximum concentrations generally at depths of about 500 m in the ocean and 20 m in Lake Ikeda.

P. R. Burkholder and L. M. Burkholder (146) found a range of 0.0027 to 0.13 and an average of 0.03 μg per l of waters along the coast of Georgia and an average of 0.042 μg per l in river water. R. J. Benoit (147) reported an average of 0.5 and a range of 0.1 to 2.0 μg per l in a New York pond. Robbins, et al., (148) found 0.060 to 0.075 μg per l at depths of 0 m to 8 m and 0.150 μg per l at 16 m in Linsley Pond, Conn.

Starr (149) found B_{12} activities 0.01 to 0.50 mμg per mg in detritus of coastal and estuarine waters and postulated net production in the marshes and net utilization in the sediments. As noted previously with sewage (83), the B_{12} concentrations showed a strong dependence on the suspended-solids content.

L. E. Ericson (150) found that marine algae concentrated B_{12} by factors of from 15 to 130 in a few days. R. Scott and Ericson (151) found evidence that B_{12} concentration in algae was dependent on photosynthesis and respiration.

Starr, et al., (152) reported that the B_{12} activity of mullet sera vary from 4.6 to 18.4 mμg per ml and of shark sera from 0 to 2.81 mμg per ml. This compares with 0.54 to 2.06 mμg per ml for humans.

Starr and F. Sanders (153) in a review of ecological aspects of B_{12} concluded that ". . . effluents from productive land masses may well contribute greatly to the productivity of distant as well as neighboring waters."

PHYSICAL AND CHEMICAL OCEANOGRAPHY

The most obvious physical features of the ocean are currents, surface waves, and temperatures. All of these are fundamentally dependent on the planetary circulation system of the atmosphere and the rotation of the earth. Evaluation of these (and other) characteristics in any coastal waters receiving municipal or industrial wastes is dependent on a knowledge of the oceanic water masses and their movements. A brief review of the general features of the oceans has been prepared by Fleming (154); more complete information is presented by Sverdrup, et al., (6) in what has been the standard work since 1942 and by G. Dieterich and K. Kalle (155).

Ocean, coastal, and nearshore currents are generally caused by wind, tides, horizontal density gradients, and wave action (6),(21),(156),(157),(158); the

relative and combined effects of these cannot be predicted for a specific waste disposal site; they must be measured. Current boundaries may be very narrow; a ½ knot change in velocity over a few tens of feet is typical of the boundary zone of the Gulf Stream (H. Stommel (159)). Where currents force two water masses together along a line of convergence, the lighter mass will override the heavier and the boundary will be marked by floating material. Divergence of water masses results in upwelling of waters from relatively shallow depths. Upwelling is also caused by wind forcing surface waters away from a shore line. Upwelled waters characteristically have lower temperatures and dissolved oxygen and higher nutrient concentrations than surface waters. Turbidity currents are due to downslope movement of dense bottom waters which carry high loadings of suspended silt and other solids; they are discussed in detail by Ph. H. Kuenen (160) and Emery (161).

Surface waves are due to local wind action and swell results from distant storms (6). Tsunamis or, popularly, "tidal waves," are due to infrequent seismic disturbances. The action of surface waves may be locally important in waste disposal in the movement of material within the surf zone (158). A more general characteristic of wave action lies in the vertical mixing of the upper waters during winter storms and the consequent diminution of temperature and density gradients; this effect is strongly noted along southern California to depths of some 200 ft (162).

Water temperatures are ultimately dependent on solar radiation; La Fond (163) has discussed the effects on surface waters of the sun, air temperature, wind, rain, waves, tides, flow over submerged dams, runoff, clouds, currents, convergence, divergence, convection cells, etc. Diurnal effects are found in the uppermost layer of, say, 1 in. in thickness while seasonal effects are reflected in the formation of a thermocline or zone of a higher temperature gradient. In coastal waters of southern California, the thermocline may be found at depths of from a few feet to as much as 100 ft (164). Long period variations in ocean temperatures are occasionally noted. In 1957-58, abnormally high temperatures were observed in Pacific coastal waters off the United States with profound effects. H. B. Stewart, et al., (165) have reported on the increase in sea level, and the California Department of Fish and Game Laboratories (166) noted the improvement of sport and commercial fishing. The warming was noted in Santa Monica Bay to extend to as much as the 150-ft depth (162).

The density structure of the ocean has important consequences in waste-disposal problems. Fundamentally the ocean is vertically stable; the density increases with depth. Unlike lakes, in which there is an annual overturning of waters and a sudden changing of water characteristics, vertical changes in various properties occur very slowly in the ocean. The greatest vertical variations in density in the ocean are found in the upper few hundred feet. Practically, density gradients in such waters are associated with temperature changes; effects of variations in salinity are generally relatively small, although they may require consideration in some localities. Density is usually expressed in oceanographic literature as sigma-T in which $\sigma_t = 1000\ (\rho - 1)$; thus for a density $\rho = 1.02345$, $\sigma_t = 23.45$. Vertical stability in the upper layers may be defined (6) as: $E' = d\sigma_t/dz$. The absolute variation of E' depends on the vertical element, dz, that is chosen; this means that since the variation of σ_t with depth is non-uniform, higher occasional values of E' will be associated with lower values of dz. The appropriate value of dz may be quite small; in the case of the floating effluent field from the 1-mile Hyperion outfall in

Santa Monica Bay, the lower boundary zone of the field is of the order of 1 ft in thickness (164). The vertical stability of a field with a dilution of 100:1 is perhaps 10 times the stability of normal coastal waters in the Bay; mixing by vertical diffusion processes is accordingly extremely small. Where a waste discharge is mixed with cold bottom water, rises to an intermediate depth and then moves down-current, the vertical stability of the field will approach that of the coastal waters. If complete homogeneity of the initial mixture is attained, the upper boundary zone will show normal stability while the lower boundary zone will have much higher stability. Numerically, values for stability (E') in the open sea range from negative or indifferent values to as much as 6×10^{-3} in which z is in meters (6). R. B. Tibby and R. D. Terry (167) reported values of from 2 to 6×10^{-6} in California coastal waters. Higher values have been found for Santa Monica Bay (164) where, in summer, E' may be as much as 2×10^{-1}.

Mixing or dilution processes are strongly affected by stability; an external source of energy is required for vertical mixing of a stratified (vertically stable) water. C. Eckert's (168) trivial example of the stirring and mixing of cream in coffee provides an excellent introduction to these processes:

". . . . Three more or less distinct stages can be observed:

1. The initial stage, in which rather large volumes of cream and coffee are distinctly visible; there are sharp gradients at the interfaces between the volumes, but elsewhere the gradient is practically zero. Averaged over the entire volume, the gradient is small. If motion of the liquid is avoided, this state persists for a considerable time.
2. The intermediate state, after motion has been induced by stirring the liquids: the masses of cream and coffee are distorted, with a rapid increase in the extent of the interfacial regions having high concentration gradients. The average value of the gradient is correspondingly increased.
3. The final state, in which the gradients disappear, apparently quite suddenly and spontaneously, with the liquid becoming homogeneous."

Eckert's model has obvious similarities to the initial dilution of a rising column of effluent which starts at the ocean floor with large amounts of potential and kinetic energy which are available for stirring. Eckert shows that advection alone will increase the mean value of any initial gradient—this is stirring. Conduction or diffusion will decrease the mean value of the gradient—this is mixing. With mixing and stirring, advection will dominate, and may so increase the mean gradient that mixing will ultimately overshadow stirring. Viscosity, unless opposed by pressure distribution, tends to stop stirring before significant mixing can occur.

The results of stirring and mixing of sewage effluent in the ocean have been examined in Santa Monica Bay. It has been observed (53) that effluent discharged 1 mile offshore into about 50 ft of water receives an initial dilution in the rising column of 20 parts sea water to 1 of effluent. The mixture at the head of the rising column or "boil" and of the field immediately downstream therefrom is not homogeneous. There are significant variations in density and other characteristics; this implies relatively high concentration gradients. Accordingly, stirring and, to a lesser extent, mixing over a period of about 4 hr result in a dilution of about 100:1. From this point on, further dilution proceeds very slowly; during the next 20 hr, mixing by lateral eddy diffusion

reaches a dilution of about 300:1. Vertical diffusion, as might be expected from stability considerations, is negligible. Stirring by waves is also insignificant; seas of some 10 ft did not alter the behavior of the effluent field.

A considerable literature on the subject of eddy diffusion has arisen over the years. Turbulent diffusion has been treated exhaustively (but not conclusively) by many workers in fluid mechanics. A variety of approaches to eddy diffusion in the ocean have been presented by Sverdrup, et al., (6), L. F. Richardson and Stommel (169), Stommel (170), W. H. Munk, et al., (171), E. Inoue (172), J. Joseph and H. Sender (173), G. T. Orlob (174), F. C. W. Olson and T. Ichiye (175), and Ichiye (176). The application of some of the concepts of eddy diffusion to the disposal of wastes in the ocean has been reported by Pearson (1),(50), J. Wright (177), N. H. Brooks (178), D. E. Carritt, et al., (179), and Gunnerson (180).

It has been found that the rate of mixing by eddy diffusion or dilution of a contaminant is proportional to the scale of the phenomenon or width of the field. This means that dilution proceeds at an ever-increasing rate. A prediction of the width of an effluent field (180) can be based on the relationship

$$e\,\frac{(W_1 + W_2)}{(2)}^{4/3} = \frac{W_2^2 - W_1^2}{32\,(t_2 - t_1)} \quad \ldots\ldots\ldots\ldots \quad (1)$$

in which W_1 and W_2 are the initial and subsequent widths of the field in centimeters at times t_1 and t_2 in seconds, respectively. The proportionality constant, e, can be taken as 0.005 or 0.0025 where lateral restraint, such as a shoreline, is absent or present, respectively.

It should be noted that dilution by either stirring or mixing is ultimately limited by the amount of new water coming into the area. This is strongly affected by the bathymetry; A. R. Miller (181) has defined four zones of mixing near the edge of the continental shelf where there is a distinct change in slope of the sea floor.

The non-linear dependence of density on temperature and salinity has been previously mentioned. This has important consequences in the mixing of different water types. It can be seen intuitively that vertical stirring in the stratified ocean requires an external source of energy such as wave action or the potential and kinetic energy of an outfall diffuser system. Horizontal mixing, which is far more important, will obtain from lateral diffusion along zones or surfaces of equal density. When two water types of equal density but different temperatures and salinities mix, the resulting mixture will have a greater density than the source waters. The density difference will not be great, rarely more than 1 part in 100,000. This is sufficient in phenomena of a relatively large scale to cause a contraction and sinking of the mixed water, a lowering of the sea surface, and horizontal (geostrophic) flow (Sverdrup, et al., (6), Dieterich and Kalle (155), and N. N. Zobov and K. D. Sabinin (182)). The significance of the contraction phenomenon has not been evaluated for waste discharges, however, it is undoubtedly small.

Dissolved oxygen (D.O.) and biochemical oxygen demand (B.O.D.) have long served as criteria for waste disposal. Since the oceans are large, it has been assumed intuitively that there is always an excess of oxygen to take care of discharges into marine waters. Where outfalls discharge into coastal waters, this is so; the discharge of 250 mgd from the 1-mile Hyperion outfall into 50 ft of water resulted in only a minor reduction of D.O. within the boil itself (56).

F. D. Bowlus (183) has speculated that the oxygen in water brought into San Francisco Bay on the rising tide is sufficient to handle the sewage from a population of 200,000,000 to 300,000,000 persons; this assumes that the discharge is completely dispersed within the tidal prism. Actually, oceanographic conditions will occasionally result in an oxygen deficiency in estuarine waters. Pearson and G. A. Holt (184) found that when coastal upwelling is present, the water entering Gray's Harbor has a characteristically low D.O. which severely limits the waste assimilating capacity of the receiving water. J. N. Carruthers, et al., (185) found similar effects along the Indian coast of the Arabian Sea where water with about 1 mg per l D.O. is brought to the surface and causes mass migrations of fish.

There is usually a small amount of B.O.D. in sea water; most of this is due to the amount of phytoplankton in the water which is also responsible for the large part of the D.O. Allen, et al., (186), have shown that as the B.O.D. increases from zero to a value of 3 mg per l in surface waters off the northern California coast, the D.O. typically rises from about 6 mg per l to about 12 mg per l.

It should be noted that recent work on the solubility of oxygen in sea water gives somewhat lower values than are shown in Standard Methods (35) with the greatest differences appearing at lower temperatures. F. A. Richards and N. Corwin (187) have prepared a convenient nomograph for determining oxygen solubilities for various values of temperature and salinity using the improved data.

Aesthetic considerations in waste-disposal operations often include the resulting appearance of the receiving water. Obvious floating materials and marked discoloration are usually proscribed by the regulating agency. Recently, receiving water standards adopted by the several water pollution control boards in California have set limits on turbidity due to the discharge. Such turbidity is measured in terms of water transparency measured by the Secchi disc. This measure is a reasonable approximation of the depth to which a casual observer can see the bottom and is accordingly of obvious interest to the general public.

There are many limitations to the Secchi disc method which have been discussed by G. E. Hutchinson (188), Tibby and Terry (167), C. E. Imel (189), and others. Secchi transparencies vary significantly with seemingly minor changes in technique. The use of a viewing tube results in larger values, while a swimmer with a face mask can see to even greater depths. Many efforts have been made to relate various photometric measurements to transparencies; for routine field observations, such attempts have not been particularly rewarding (189). Secchi disc observations continue to be made, usually from the deck of a boat without a viewing tube, and the data therefrom can be satisfactorily analyzed. The effects of distance from shore, various water masses, and plankton on transparency in coastal waters has been discussed by Emery (190). In Santa Monica Bay, it has been shown (83) that the greatest reduction in transparency is due to surf action. Of somewhat lesser importance are the plankton densities; the effect of the suspended solids from the Hyperion discharge is relatively minor.

The penetration of light into the sea has received considerable attention in studies of photosynthesis (6), (13). Duntley (12) has measured light attenuation in the open sea to depths of about 1,800 ft. Although light is completely absorbed by a much shallower water layer near the coasts, that light which does reach the sea bottom is essential for growth of attached algae. North

and Clendenning (96),(97) have accordingly investigated minimum light requirements for young plants with particular attention to the direct and indirect effects of waste discharges.

Geological investigations of the ocean floor are significant not only in studies of foundation conditions for submarine structures, but for evaluation of biological observations of benthic plants and animals. Barnard, Hartman, Jones (92), and Hartman (93) have shown that the presence or absence of certain animal species and assemblages is strongly dependent on both grain size and mineral composition of the substrate. It follows that analysis of biological data must include consideration of the sediments themselves.

Sedimentation processes in the ocean have been studied by geologists for many years (6),(160),(161). Only recently have the coagulating effects of sea water on clay minerals been examined; V. G. Whitehouse, et al., (191),(192), (193),(194) have reported the effects of salinity, temperature, ions of heavy metals, carbohydrates, proteins, humic acids, pH, and mineral concentration gradients on the settling velocities of kaolinite illite and montmorillonite. Gunnerson (195) has discussed the application of these works to waste-disposal problems. It is reasonable to expect that at least a portion of the suspended solids in an effluent will respond to various environmental factors in manners similar to those of natural mineral compounds.

The fate of organic material in an effluent is imperfectly known; some is undoubtedly adsorbed onto surfaces of inorganic solids. Alkyl benzene sulfonate which is discharged into Santa Monica Bay in quantities of some 8 tons per day (83) has no apparent effect. It is reasonable to assume that the alkyl benzene sulfonate is partially, if not entirely, adsorbed onto those particles; the work of C. E. Renn and M. F. Brada (196) suggests that there are probably a sufficient number of silt and clay-size particles in most effluents or receiving waters to adsorb observed alkyl benzene sulfonate concentrations.

The significance of surface waves in waste disposal has been discussed previously; mention should also be made of internal waves. Such waves are found at all depths in the oceans and are detected by observing periodic variations in temperature or density. The predominating internal waves in surface waters to, say, 100 ft have tidal periods. Others show a large range of periods, with some a short as a few minutes. G. Ewing (197) and La Fond (198) have shown that internal waves within the upper 10 ft to 30 ft are reflected in surface slicks which may be observed moving shoreward in the same manner as, although at a lesser velocity than, surface swell; such waves typically have an amplitude of from 2 ft to 10 ft. Internal wave amplitudes vary directly with depth; Sverdrup, et al., (6) discuss waves in the Atlantic Ocean at about 1,800 ft with an amplitude of some 100 ft. Amplitudes of as much as 200 ft have been observed in 800-ft depths in San Pedro Channel off southern California (199). Emery (161) has reported standing waves off southern California in Catalina Basin which has a sill depth of over 3,200 ft; here the amplitude was about 150 ft.

Internal waves have essentially the same characteristics as surface waves. A. Defant (200) gives evidence for internal breaking of waves in the open sea, and routine temperature observations in Santa Monica Bay (201) have indicated occasional internal surf in the upper layers. It may be speculated that internal rip-currents may be associated with internal surf. Stommel (159) has suggested that even internal hydraulic jumps may occur.

The significance of internal waves in waste disposal lies in the evaluation of oceanographic data (Defant (202)) and in the stirring of the receiving waters

at depth. If internal rip currents exist, they may trigger turbidity currents. Evidence for frequent turbidity currents along the San Pedro Channel has been found (199) in the fine silt content in water samples taken along the continental slope at depths between 600 ft and 900 ft; one series of observations indicated that shallow water plankton had been entrained in the turbidity current and carried down-slope from initial depths of less than 300 ft to some 800 ft. Such action may explain the observed periodic movement of sediment from the Hyperion 7-mile outfall down-slope from an initial 300 ft to 600 ft or more (83).

ESTUARIES AND SEMI-ENCLOSED BAYS

The distinguishing characteristic of estuaries and semi-enclosed bays, including harbors, is that each requires specific studies. Such waters vary widely not only among apparently similar locations, but within the confines of any one body.

General classifications of estuaries have been made; those of Pritchard (203) are particularly useful. Other general studies of estuarine environments are available; Emery and Stevenson (204) have discussed their physical and chemical characteristics and Hedgepeth (205) has reviewed their biological aspects.

Several approaches to the problem of the mixing of the fresh and salt water have been developed and have recently been reviewed by D. J. O'Connor (206) in a study of estuarine oxygen balances.

Model studies on Puget Sound have been reported by Maurice Rattray, Jr., and J. H. Lincoln (207) and C. A. Barnes, et al., (208). R. Kent (209) has examined diffusion in a model of Delaware Bay. H. B. Simmons (210) has reviewed the limitations of model studies in pollution analyses.

J. S. Creager (211) has emphasized that deposition of bed load can be expected in the zone where opposing river and tidal currents meet. Bruce W. Nelson (212) has examined the transport of colloidal sediment and found that such sediments are peptized in the lowest salinity zone and that reflocculation may be negligible in an estuary discharging sufficient quantities of fresh water because of time considerations.

J. P. Tully (213) and M. Waldichuk (214) reported the basis for design and the results, respectively, of an outfall discharging pulp mill wastes in Alberni Harbor, British Columbia. In this case, the outlet was located at the surface rather than at depth in order that the effluent would move seaward with the river water.

W. V. Burt and L. D. Marriage (215) have shown for the Yaquina River Estuary that as an outfall is moved seaward, the maximum concentration of a pollutant is decreased rapidly. However, tidal movement will still move some of the pollutant well upstream, from, say, 15 miles to 20 miles from the ocean, while the outfall may be from 1 mile to 12 miles from the ocean.

Ilmo Hela, et al., (216) have demonstrated that knowledge of the hydrography is necessary in characterizing the recovery of Biscayne Bay to normal conditions after the 50 mgd discharge of raw sewage from Miami was diverted to the ocean.

P. Bruun (217), (218) has emphasized the importance of the shape of bay fills in Florida so as to avoid stagnation. It may be noted that this may be particularly significant in subdivided areas served by private disposal systems.

L. C. Larson (219) has reviewed water use and water quality criteria in Los Angeles and Long Beach Harbors, E. F. Corcoran and J. S. Kitteredge (220) have shown that one of the effects of the discharge of sewage effluent into San Diego Bay has been severe water-line corrosion of ships due to high dissolved oxygen produced by phytoplankton in the nutrient-enriched waters.

A unique problem in estuarine hydrography is found in Lake Washington where salt water enters through the locks on the ship canal. Rattray, et al., (221) have found evidence that the increasing salinity in bottom waters may ultimately be expected to prevent annual overturn and flushing.

DESIGN AND CONSTRUCTION

Pearson (1) has reviewed design criteria and construction materials and methods for ocean outfalls built prior to 1955. Hyperion engineers (222) has compiled a more recent summary of this information.

Outfalls have generally been built from construction piers and trestles. D. L. Narver, Jr. and E. H. Graham (223), and D. R. Miller (224) have described the laying of the 7-mile digested sludge outfall at Hyperion in $7\frac{1}{2}$ days; the operation of this line has been discussed by Hume, et al., (225). The pulling method used at Hyperion has also been used for a water line to two islands off the coast of Venezuela (226) and for a 19-mile oil line in the Persian Gulf (227).

The cathodic protection system employed at Hyperion is described by H. J. Keeling (228). The selection of biologically resistant materials for submarine cables has been treated by L. R. Snoke (229). In some cases, the nature of the waste may dictate the use of similar resistant materials; a 12-in. rubber pipe was found necessary to carry nitric and sulfuric acid wastes to the channel of the lower Delaware River (230).

Pomeroy (231) has pointed out that proposed ocean outfalls must be frequently evaluated without extensive oceanographic surveys because of the time and expense of the latter. He has proposed an empirical formula which is based on observed bacteriological conditions around outfalls in comparable locations:

$$N = \frac{K Q^2}{Y X^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

in which N is the maximum shore pollution expressed as the arithmetic mean or 80-percentile; Q denotes the average flow; Y is the depth of discharge; X represents the distance from shore; and K is a proportionality constant which has been found to vary from 5×10^6 to 10×10^6 when units are in feet and gallons.

AM Rawn, F. R. Bowerman, and Brooks (232) have reviewed model studies, hydraulic design, and operating characteristics of the several outfalls from the Los Angeles County Sanitation Districts treatment plant. They present a graphic solution for minimum dilution at the head of the rising column as a function of water depth, diameter of pipe, and Froude number.

SPECIAL STUDIES AND CURRENT RESEARCH

During the past few years, a large amount of research has been done on the disposal of radioactive waste into the oceans. While much of the work is

relevant only to batch discharges into the deep sea, a large amount of the data is applicable to continuous discharges into coastal waters. It may be noted that radioactive discharges into coastal waters already exist. Not only is it certain that typical municipal effluents must reflect medicinal uses of radioisotopes, but that the increased use of these materials for industrial purposes will necessarily result in greater quantities being discharged into sewerage systems. Even by 1959, the Windscale atomic plant in Great Britain was permitted to discharge as much as 10,000 curies per month through a 3-mile outfall into the Irish Sea (179).

The basic report by Roger Revelle, et al., (233) includes data on wastes from the atomic power industry; mixing; effects of ecological systems on transport and accumulation of various elements, of which non-radioactive isotopes are normally found in many municipal and industrial discharges; and precipitation of various ions by physical, chemical, and biological processes.

Carritt, et al., (179) studied twenty-eight proposed disposal sites in Atlantic and Gulf coastal water. Pritchard, et al., (234) have developed criteria for disposal of wastes from nuclear powered ships into harbor, coastal, and offshore waters.

The use of radioactive tracers in studying Hyperion sewage effluent fields has been previously noted (47). Additional data on this work, which involved the release of 20 curies of scandium-46, has been reported by R. L. Ely, Jr. (235) and E. I. Goodman (236).

Disposal of acid chemical wastes from barges off the New Jersey coast has been examined by Ketchum and W. L. Ford (237) and Redfield and L. A. Walford (238). J. W. Eberman (239) and D. W. Hood, et al., (240) have studied disposal by barges of chlorinated hydrocarbon wastes in the Gulf of Mexico. F. Beyer (241) has reported on the dispersal of sewage sludge from a barge in Oslo Fjord.

The quantity and characterization of coastal oil pollution has been reported by R. C. Merz (242) and A. A. Rosen, et al., (243). It has been found that most of the tarry deposits on beaches are from natural sources and that oil from submarine seeps can generally be distinguished from crudes.

Theoretical and experimental studies of circulation, renewal rates, and diffusion in Baltimore Harbor, Chesapeake Bay, and New York Harbor are being made by the Chesapeake Bay Institute of Johns Hopkins University. Pritchard (244) has indicated that these studies will provide criteria for various waste disposal operations.

There are at present (1960) two locations where it is possible to study the return of an area which was formerly strongly affected by raw or treated sewage to normal. These include the nearshore areas of Santa Monica Bay, and the whole of Biscayne Bay, where studies are being made by the City of Los Angeles (83) and by the University of Miami (245), respectively. In the future, San Diego Bay may be added to the list. The times required for the return of these areas to normal will be of great significance since the duration of effects from other existing or proposed discharges can then be estimated. There are no presently available (1960) data on this subject.

Because of the necessity for developing and subsequently evaluating design criteria for additional capacity in the Hyperion Treatment Plant, Santa Monica Bay has probably become the best-known body of water of its size in the world. The investigations were begun in 1954, and have included oceanography (246), (247), biology (84), (248), bacteriology (47), (56), geology (249), and sanitary

engineering (56),(83),(222),(225). Observations are being made to assure compliance with receiving water standards (250) and more adequately characterize the stabilization of the effluent in the ocean. Garber (251) has noted that such work is a logical part of sewage treatment and disposal since the burden of proof of the effects of the effluent is generally on the discharger.

Similar, though somewhat less comprehensive, studies have been made for the City of San Diego. A major survey of near shore currents has been reported by R. D. Gaul and Stewart, Jr. (252). In this survey, currents were measured at the surface and at depth by means of drogues or current crosses. The survey differed in this respect from the Santa Monica Bay studies where drift cards (247) and current meters (30) were used independently and found to give consistently comparable results (222). One feature of the San Diego study was the computation of depths at which 50:1 and 100:1 dilutions would stratify (31). I. Nusbaum, et al., (253) had previously noted the northerly drift of pollution from the Tijuana River and speculated that the movement was due to wave action and the resulting longshore currents. However, this movement corresponds with similar northerly or up-coast movement from the 1-mile outfall in Santa Monica Bay where the littoral drift is predominantly down-coast. The northerly movement of the effluent field is quite probably due to geostrophic flow where the lighter (effluent) water is on the righthand side of the current (254).

In addition to the local studies of the Los Angeles and San Diego areas, a major 4-yr survey of the coastal waters and underlying continental shelf off the southern California coast between Point Conception and the Mexican border was begun in 1957 by the Allan Hancock Foundation, University of southern California, for the California State Water Pollution Control Board. An interim report on this survey has been published (255) which, with a final report to be available in 1961 (or so), will provide basic data for the evaluation of the effects of waste discharges into these waters. The survey includes meteorology, oceanography, geology, and planktonic and benthic biology.

The California State Water Pollution Control Board is currently sponsoring other studies, some of which have been mentioned in earlier sections of this review. These include studies of the effects of waste discharges on kelp at the Scripps Institution of Oceanography (96),(97); an oceanographic survey of some northern California coastal waters at Humboldt State College (186); tracer techniques and engineering evaluation and development of bioassay methods at the University of California; and collation, evaluation, and presentation of scientific and technical data by Engineering-Science, Inc., Arcadia, Calif. A summary of the accomplishments to date of state-sponsored projects is in press (256). The summary notes that the net changes in drainage to the sea due to steadily increasing urbanization include an increase in the total discharge, a leveling out of the rates of discharge, a decrease in the sediment carried to sea, and an increase in the nutrients. Such changes are probably characteristic of littoral waters throughout the world as coastal populations increase, and are invariably reflected in the ecology of such waters. Similar changes have already occurred and have been rather thoroughly studied in surface streams along which cities have historically developed. It is suggested that the concept of a waste-assimilating or self-purification capacity of a body of water has serious limitations in a changing environment; there is an inherent finality, usually unwarranted, in such an approach. A more satisfactory position derives from adequate knowledge of the changes caused by

any given discharge, which can be stated in terms of the response of the receiving water and its life.

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APPENDIX.—BIBLIOGRAPHY

1. "An Investigation of the Efficacy of Submarine Outfall Disposal of Sewage and Sludge," by E. A. Pearson, Publication No. 14, State of California Water Pollution Control Board, Sacramento, California, 1956.
2. "Discharge of Wastes into the Sea in European Coastal Areas," P. Koch, in Reference 4, in press.
3. "Proceedings, Second Seminar on Biological Problems in Water Pollution," USPHS, Robert A. Taft, Sanitary Engineering Center, Cincinnati, Ohio, in press.
4. "Proceedings, First International Conference on Waste Disposal in the Marine Environment, July, 1959," University of California Press, Berkeley, California, in press.

5. "Proceedings, Sixth Annual Symposium on Water Pollution Research: Oceanography and Related Pollution Problems of the Northwest," by E. F. Eldridge, et al, USPHS, Region IX, Portland, Oregon, 1959.

6. "The Oceans," by H. U. Sverdrup, M. W. Johnson, and R. H. Fleming, Prentice-Hall, 1942.

7. "Limnological Methods," by P. S. Welch, Blakiston, Philadelphia, Pa., 1948.

8. "Instruction Manual for Oceanographic Observations," U. S. Navy Hydrographic Office Publication H.O. 607, 2nd Ed., 1955.

9. "Oceanographic Instrumentation," J. D. Isaacs and C. O'D. Iselin, Eds., National Academy of Sciences-National Research Council Pub. No. 309, 1952.

10. "Oceanographic Instrumentation," by A. C. Vine, Science, Vol. 122, 1955, pp. 748-751.

11. "Physical and Chemical Properties of Sea Water," R. C. Vetter, et al, National Academy of Sciences-National Research Council Pub. No. 600, 1959.

12. "The Penetration of Sight into the Sea," by S. Q. Duntley, in "Aspects of Deep-Sea Research," National Academy of Sciences-National Research Council Pub. No. 473, 1957, pp. 79-89.

13. "Solar Radiation, Submarine Daylight, and Photosynthesis," by R. W. Holmes, Geological Society of America, Memoir 67, Vol. 1, 1957, pp. 109-128.

14. "The Chemistry and Fertility of Sea Water," by H. W. Harvey, Cambridge University Press, Cambridge, England, 1955.

15. "A Field and Laboratory Manual of Oceanographic Procedures," by Staff, Allan Hancock Foundation, University of Southern California, Los Angeles, California, 1958 (multilith).

16. "Apparatus and Methods of Oceanography, Part One: Chemical," by H. Barnes, Interscience, New York, 1959.

17. "A Bathythermograph," by A. F. Spilhaus, Journal of Marine Research, Vol. 1, No. 2, 1938, pp. 95-100.

18. Hytech Corporation, 6803 West Blvd., Inglewood 3, California.

19. "Marine Microbiology," by C. E. Zo Bell, Chronica Botanica, 1946.

20. "The Principles of Measuring Currents," by G. Böhnecke, Association d'Oceanographie Physique, Publication Scientifique No. 14, 1955, 28 pp.

21. "Investigation of Current Measurement in Estuarine and Coastal Waters," by J. W. Johnson and R. L. Weigel, State of California Water Pollution Control Board Publication No. 19, Sacramento, Calif., 1959.

22. "Manual of Tide Observations," U. S. Coast and Geodetic Survey Spec. Pub. No. 196, 1941.

23. "Manual of Current Observations," U. S. Coast and Geodetic Survey Spec. Pub. No. 215, 1950.

24. "The Direct Measurement of Subsurface Currents in the Oceans," by K. F. Bowden, Deep Sea Research, Vol. 2., No. 1, 1954, pp. 33-47.

25. "Wind-generated Ocean Currents at Amrum Bank Lightship," by H. Mandelbaum, Transactions, American Geophysical Union, Vol. 36, No. 1, 1955, pp. 72-86.

26. "Wind Influence on a Rotary Tidal Current," by H. Mandelbaum, Transactions, American Geophysical Union, Vol. 38, No. 6, 1957, pp. 867-878.

27. "Measurement and Data Reduction of Ocean and Estuary Currents," by R. L. Weigel and J. W. Johnson, in Reference 4, in press.

28. "The Relationship between Local Wind and Water Movement in Coastal Waters of the British Isles," by V. F. C. Veley, in Reference 4, in press.

29. 1958 Report of the Interstate Sanitation Commission, 10 Columbus Circle, New York, N. Y., 1959 (mimeo.).

30. "Summary Report, Oceanographic Investigation of Santa Monica Bay," Bureau of Sanitation, City of Los Angeles, California, 1956 (mimeo.).

31. "Oceanographic Surveys for the City of San Diego, 1956-1957," by Geological Diving Consultants, Inc., San Diego, Calif., 1957.

32. "Statistical Theory of Extreme Values and Some Practical Applications," by E. J. Gumbel, National Bureau of Standards, Applied Mathematics Series No. 33, Washington, D. C., 1954.

33. "Processing Oceanographic Data," by E. C. La Fond, U. S. Navy Hydrographic Office Publication H.O. 614, Washington, D. C., 1951.

34. "Tables for Sea Water Density," U. S. Navy Hydrographic Office Publication H.O. 615, Washington, D. C., 1952.

35. "Standard Methods for the Examination of Water, Sewage, and Industrial Wastes," H. A. Faber, W. D. Hatfield, M. H. McCrady, and E. K. Kline, Editors, 10th Ed., American Public Health Assoc., 1955.

36. "Obtaining Ecological Data in the Sea," by J. W. Hedgepeth, G. Thorsom, and G. Gunter, Geological Society of America Memoir 67, Vol. 1, 1957, pp. 53-86.

37. "Oceanography and Marine Biology," by H. Barnes, McMillan, 1959.

38. "The Status of Plankton Determination in Marine Pollution Analysis," by J. B. Lackey, in Ref. 4, in press.

39. "Fishery Science, Its Methods and Applications," by G. A. Rouncefell and W. H. Everhart, Wiley, 1953.

40. "Some Experiments on Factors Influencing Mesh Selection in Trawls," by L. K. Boerema, Journal du Conseil pour l'Exploration de la Mer, Vol. 21, No. 2, 1956, pp. 175-191.

41. "Quantitative Sampling of Marine Fishes—A Problem in Fish Behavior," by G. H. Allen, A. D. DeLacy, and D. W. Gotshall, in Ref. 4, in press.

42. "Survey Techniques for Benthic Biology," by J. L. Barnard and G. F. Jones, in Ref. 4, in press.

43. "Pollution Monitoring and Prevention by Use of Bivariate Control Charts," by T. W. Beak, C. de Courval, and N. E. Cooke, Sewage and Industrial Wastes, Vol. 31, No. 12, 1959, pp. 1383-1394.

44. "Description of a Community of Microorganisms in Purified Sewage Mixed with Rain Water from Storm Sewers," by Th. G. N. Dresscher, Hydrobiologica, Vol. 14, No. 2, 1959, pp. 189-204.

45. "Nitrite in Polluted Sea-Water," by T. Braarud and E. Føyn, Avhandliger utgitt av Det Norske Videnskaps-Akademi i Oslo, I. Mat.-Naturv. Klasse, 1951, No. 3.

46. "Progress Report No. 3, Oceanographic Investigation of Santa Monica Bay," Bureau of Sanitation, City of Los Angeles, California, 1956 (mimeo.).

47. "Studies on Coliform Bacteria Discharged from the Hyperion Outfall," by S. C. Rittenberg, Allan Hancock Foundation, University of Southern California, Los Angeles, California, 1956 (multilith).

48. "The Use of Radioactive and Bacterial Tracers to Follow Sewage Pollution in the Sea," by J. L. Putnam, A. M. Wildblood, and J. E. Robson, The Water and Sanitary Engineer, Sept/Oct 1956, pp. 99-101.

49. "Sewage Effluent Dilution in Sea Water," by C. H. Lawrance, Water and Sewage Works, March 1958, pp. 116-122.

50. "Tracer Methodology and Pollutional Analyses of Estuaries," by E. A. Pearson, in Ref. 4, in press.

51. "An Improved Fluorescent Tracer for Studies of Water Movement and Dispersion," by J. H. Carpenter, paper presented at 41st Annual Meeting, American Geophysical Union, Washington, D. C., 1960. Abstract, Journal of Geophysical Research, in press.

52. "Some Preliminary Results of Direct Observations of Water Movement and Dispersion using a New Fluorescent Tracer Technique," by D. W. Pritchard, paper presented at 41st Annual Meeting, American Geophysical Union, Washington D. C., 1960. Abstract, Journal of Geophysical Research, in press.

53. "Hydrographic Manual," United States Coast and Geodetic Survey Special Publication No. 143, 1942.

54. "International Symposium on Electronic Distance Measuring Techniques," edited by C. A. Whitten and E. Schmid, Journal of Geophysical Research, Vol. 65, No. 2, 1960, pp. 385-528.

55. "Sources of Limnological and Oceanographic Apparatus and Supplies," by J. H. Ryther, C. S. Yentsch, and G. H. Lauff, Limnology and Oceanography, Vol. 4, No. 3, 1959, pp. 357-365.

56. "Sewage Disposal in Santa Monica Bay, California," by C. G. Gunnerson, Transactions, ASCE, Vol. 124, 1959, pp. 823-851.

57. "Investigation on the Source and Area of Contamination in Tokyo Bay," by Y. Sekine, J. Takeuchi," and K. Ineue, Journal of the Tokyo University of Fisheries, Vol. 43, No. 2, 1957, pp. 183-197.

58. "Investigation on the Source and Area of Contamination in Tokyo Bay," by Y. Sekine, T. Yoshida, and T. Yoshizawa, Journal of the Tokyo University of Fisheries, Vol. 44, No. 1-2, 1958, pp. 91-103.

59. "Pollution of the Rhine and Its Influence on Netherlands Beaches," by J. G. W. Bolomey, in Ref. 4, in press.

60. "Evaluating Bacterial Contamination in Sea Water Samples," by G. T. Orlob, Public Health Reports, Vol. 71, No. 12, 1956, pp. 1246-1252.

61. "Comparison of the MF and MPN Techniques in Examining Sea Water," by M. W. Presnell, W. Arcisz, and C. B. Kelly, Public Health Reports, Vol. 69, No. 3, 1954, pp. 300-304.

62. "Simultaneous Determination of Coliform and Escherichia coli Indices," by M. Levine, R. H. Tanimoto, H. Minette, J. Arakaki, and G. B. Fernandes, Applied Microbiology, Vol. 3, 1955, pp. 310-314.

63. "Studies on the Use of Membrane Filters for the Estimation of Coliform Densities in Sea Water," by W. L. Henderson, Sewage and Industrial Wastes, Vol. 31, No. 1, 1959, pp. 78-91.

64. "Bacterial Populations in Sea Water as Determined by Different Methods of Enumeration," by H. W. Jannash and G. E. Jones, Limnology and Oceanography, Vol. 4, No. 2, 1959, pp. 128-139.

65. "Graphical Approach to Statistics, IV. Evaluation of Bacterial Density," by C. J. Velz, Water and Sewage Works, Vol. 98, 1951, pp. 66-70.

66. "Statistical Analysis of Coliform Data," by H. A. Thomas, Jr., Sewage and Industrial Wastes, Vol. 27, No. 2, 1955, pp. 212-222.

67. "Statistical Treatment of Bacterial Data," by R. Pomeroy, Sewage and Industrial Wastes, Vol. 27, No. 1, 1955, pp. 85-92.

68. "On the Probability of Survival of Bacteria in Sea Water," by E. K. Harris, Biometrics, Vol. 14, No. 6, 1958, pp. 195-206.

69. "How Probable is the Most Probable Number," by R. L. Woodward, Journal, American Water Works Association, Vol. 49, 1957, pp. 1060-1068.

70. "Factors Affecting the Survival of Bacteria in Sea Water," by A. F. Carlucci and D. Pramer, Applied Microbiology, Vol. 7, No. 6, 1959, pp. 388-392.

71. "Coliform Bacteria in Sediments around Three Marine Sewage Outfalls," by S. C. Rittenberg, T. Mitwer, and D. Ivler, Limnology and Oceanography, Vol. 3, No. 1, 1958, pp. 101-108.

72. "Nature of the Bactericidal Agent in Sea Water," by J. K. Johanneson, Nature, Vol. 180, 1957, pp. 285-286.

73. "Iodate-iodine and Total Iodine Content of Sea Water," by R. A. Barklay and T. G. Thompson, Preprints International Oceanographic Congress, American Association for the Advancement of Science, Washington, D. C. 1959, pp. 813-814.

74. "The Production of Antibiotics by Plankton Algae and Its Effect upon Bacterial Activities in the Sea," by E. Steemann Nielsen, Papers in Marine Biology and Oceanography, Pergammon Press, London, 1955, pp. 281-286.

75. "Bacteriophage," by J. S. K. Boyd, Cambridge University Biological Reviews, Vol. 31, No. 1, 1956, pp. 71-107.

76. "Characteristics and Expeditious Determination of Bacterial Indices of Pollution of Marine Bathing Beaches," by M. Levine, H. Minette, and R. H. Tanimoto, in Ref. 4, in press.

77. "Bacteriological Standards for Bathing Waters, by W. F. Garber, Sewage and Industrial Wastes, Vol. 28, No. 6, 1956, pp. 795-808.

78. "Recent British Work on the Risk of Infection through Bathing in Sewage-polluted Sea Water," by B. Moore, in Ref. 4, in press.

79. "Sewage Contamination of Coastal Bathing Waters in England and Wales," by the Committee on Bathing Beach Contamination of the Public Health Laboratory Service, B. Moore (Chairman), Journal of Hygiene, Vol. 57, No. 4, 1959, pp. 435-472.

80. "Oxygen, Phosphate, and Nitrate in the Atlantic Ocean," by G. A. Riley, Bulletin of the Bingham Oceanographic Coll. 13, 1951.

81. "Regeneration of Nutrients in Sediments of Marine Basins," by S. C. Rittenberg, K. O. Emery, and W. L. Orr, Deep-Sea Research, Vol. 3, 1955, pp. 23-45.

82. "Nutrient Budgets in the Ocean," by K. O. Emery, S. C. Rittengerg, and W. L. Orr, Essays in the Natural Sciences in Honor of Captain Allan Hancock, University of Southern California Press, Los Angeles, California, 1955, pp. 299-309.

83. "Characteristics and Effects of Hyperion Effluent in Santa Monica Bay, California," by N. B. Hume, C. G. Gunnerson, and C. E. Imel, paper presented at Annual Meeting, Pacific Section, American Geophysical Union, Los Angeles, California, 1960.

84. "Contributions to a Biological Survey of Santa Monica Bay, California," by O. Hartman, Allan Hancock Foundation, University of Southern California, Los Angeles, California, 1956 (multilith).

85. "Sewage in Santa Monica Bay: A Critical Review of the Oceanographic Studies," Marine Advisers, La Jolla, California, 1956 (multilith).

86. "Plankton and Associated Nutrients in the Waters Surrounding Three Sewer Outfalls in Southern California," by R. E. Stevenson and J. R. Grady, Allan Hancock Foundation, University of Southern California, Los Angeles, California, 1956 (multilith).

87. "The Relation of Polychaetous Annelids to Harbor Pollution, by D. J. Reish, Public Health Reports, Vol. 70, No. 12, 1955, pp. 1168-1174.

88. "Effect of Pollution on Marine Life," by D. J. Reish, Industrial Wastes, Sept.-Oct., 1957, pp. 114-118.

89. "An Ecological Study of Pollution in Los Angeles-Long Beach Harbors, California," by D. J. Reish, Allan Hancock Foundation Occasional Paper 22, University of Southern California, Los Angeles, California, 1959.

90. "The Use of Marine Invertebrate Populations as Indicators of Water Quality," by D. J. Reish, in Ref. 4, in press.

91. "Marine Pollution," by D. J. Reish and J. L. Barnard, Water and Sewage Works, No. 6, 1959.

92. "Benthic Biology of the Mainland Shelf of Southern California," by J. L. Barnard, O. Hartman, and G. F. Jones, State of California Water Pollution Control Board, Sacramento, California, Publication No. 20, 1959, pp. 265-429.

93. "The Benthic Fauna of Southern California in Shallow Depths and Possible Effects of Wastes on the Marine Biota," by O. Hartman, in Ref. 4, in press.

94. "Microbiology of the Mainland Shelf of Southern California," by J. M. Resig, State of California Water Pollution Control Board, Sacramento, California, Publication No. 20, 1959, pp. 431-560.

95. "Foraminiferal Ecology around Ocean Outfalls Off Southern California," by J. M. Resig, in Ref. 4, in press.

96. "The Effects of Waste Discharges upon Kelp," by W. J. North, K. A. Clendenning, et al; Institute of Marine Resources, University of California, La Jolla, California, IMR Reference Numbers 58-2, 58-6, 58-11, 1958; 59--1, 59-4, 59-8, 59-11, 1959.

97. "Effects of Wastes on the Giant Kelp, Macrocystis pyrifera," by K. A. Clendenning and W. J. North, in Ref. 4, in press.

98. "A History of the Kelp Areas in Southern California near Submarine Outfalls," by W. J. North, 1960 (manuscript).

99. "Mineral Nutrition of Phytoplankton," by B. H. Ketchum, Annual Review of Plant Physiology, Vol. 5, 1954, pp. 55-74.

100. "The Marine and Fresh Water Plankton," by C. C. Davis, Michigan State University Press, 1955.

101. "Plankton," by M. W. Johnson, Geological Society of America, Memoir 67, Vol. 1, 1957, pp. 443-460.

102. "Nutrient Elements," by H. Barnes, Geological Society of American, Memoir 67, Vol. 1, 1957, pp. 297-344.

103. "An Ecological Survey of the Tropical Waters adjacent to Miami," by F. G. W. Smith, R. H. Williams, and C. C. Davis, Ecology, Vol. 31, No. 1, 1950, pp. 119-146; summarized in Davis (97).

104. "The Algal Vegetation of Oslo Fjord," by O. Sundence, Skr, norsk Vidensk Akad, 1953, No. 2; Abstract, Water Pollution Abstracts, Vol. 28, No. 8, 1955, p. 285.

105. "Chemical and Biological Effects of Sewage Disposal in Inner Oslo-Fjord," by E. Føyn, in Ref. 4, in press.

106. "Water Pollution in the Port of Marseilles and Its Relation to the Flora and Fauna," by R. Gilet, in Ref. 4, in press.

107. "Plankton and Industrial Pollution in Cleveland Harbor," by C. C. Davis, Sewage and Industrial Wastes, Vol. 27, No. 7, 1955, pp. 835-850.

108. "Artificial Eutrophication of Lake Washington," by W. T. Edmoudson, G. C. Anderson, and D. R. Peterson, Limnology and Oceanography, Vol. 1, No. 1, 1956, pp. 47-53.

109. "A Source of Phosphorus for the Western Basin of Lake Erie," by H. Curl, Jr., Limnology and Oceanography, Vol. 2, No. 4, 1957, pp. 315-320.

110. "Comparative Studies on the Metabolism of Marine Waters," by H. T. Odum and C. M. Hoskin, Institute of Marine Science, University of Texas, Vol. 5, 1958, pp. 16-46.

111. "Diurnal pH Variation in Texas Bays, and Its Application to Primary Production Estimation," by K. Park, D. W. Hood, and H. T. Odum, Institute of Marine Science, University of Texas, Vol. 5, 1958, pp. 47-61.

112. "Analysis of Diurnal Oxygen Curves for the Assay of Reaeration Rates and Metabolism in Polluted Marine Bays," by H. T. Odum, in Ref. 4, in press.

113. "Photosynthesis in Sewage Treatment," by W. J. Oswald and H. B. Getaas, Transactions, ASCE, Vol. 122, 1957, pp. 73-105.

114. "Trickling Filter Ecology," by W. B. Cooke, Ecology, Vol. 40, No. 2, 1959, pp. 273-291.

115. "Snails Associated with Sewage Treatment Installations," by W. M. Ingram, W. B. Cooke, and L. I. Hagerty, Sewage and Industrial Wastes, Vol. 30, No. 6, 1958, pp. 821-825.

116. "Mass Mortality in the Sea," by M. Brongersma-Sanders, Geological Society of America, Memoir 67, Vol. 1, 1957, pp. 941-1010.

117. "The Size, Shape, and Density of Marine Phytoplankton Concentrations," by Richard Bainbridge, Cambridge University Biological Reviews, Vol. 32, 1957, pp. 91-115.

118. "Interrelations of Organisms. A. Commensalism," by R. P. Dales, Geological Society of America, Memoir 67, Vol. 1, 1959, pp. 391-412.

119. "Interrelations of Organisms. B. Parasitism," by B. H. Hopkins, Geological Society of America, Memoir 67, Vol. 1, 1957, pp. 413-428.

120. "Interrelations of Organisms. C. Symbiosis," by C. M. Yonge, Geological Society of America, Memoir 67, Vol. 1, 1959, pp. 429-442.

121. "Squamous Papilloma in the White Croaker," by F. E. Russell and P. Kutin, Journal of the National Cancer Institute, Vol. 18, No. 6, 1957, pp. 857-860.

122. "Transactions, Seminar on Biological Problems in Water Pollution, April 23-27, 1956," C. M. Tarzwell, Editor, USPHS, Robert A. Taft Sanitary Engineering Center, Cincinnati, Ohio, 1957.

123. "Protozoa as Indicators of the Ecological Condition of a Body of Water," by J. B. Lackey, Ref. 122, 1957, pp. 30-59.

124. "Algae as Biological Indicators of Pollution," by C. M. Palmer, Ref. 122, 1957, pp. 60-69.

125. "Use and Value of Fungi as Biological Indicators of Pollution," by W. B. Cooke, Ref. 122, 1957, pp. 84-93.

126. "Use and Value of Biological Indicators of Pollution: Fresh Water Clams and Snails," by W. M. Ingram, Ref. 119, 1957, pp. 94-135.

127. "The Use and Value of Acquatic Insects as Indicators of Organic Enrichment," by R. R. Gaufin, Ref. 119, 1957, pp. 136-143.

128. "Biological Indices of Water Pollution, with Special Reference to Fish Populations," by P. Doudoroff, Ref. 119, 1957, pp. 144-163.

129. "Biological Considerations—the Fourth Phase," by A. C. Redfield, in Ref. 11, 1959, pp. 101-112.

130. "Some New Aspects of Phosphates in Relation to Lake Fertilization," by C. N. Sawyer, Sewage and Industrial Wastes, Vol. 24, No. 6, 1952, pp. 768-776.

131. "The Final Step in Sewage Treatment," by Karl Imhoff, Sewage and Industrial Wastes, Vol. 27, No. 3, 1955, pp. 332-335.

132. "Effects of Fertilization of Receiving Waters," by J. B. Lackey, Sewage and Industrial Wastes, Vol. 30, No. 11, 1958, pp. 1411-1416.

133. "Chemical and Biological Aspects of Sewage Disposal in Inner Oslo Fjord," by E. Føyn, in Ref. 4, in press.

134. "Activated Sludge as a Source of Vitamin B_{12} for Animal Feeds," by S. R. Hoover, L. Jasewicz, J. B. Pepinsky, and N. Porges, Sewage and Industrial Wastes, Vol. 24, No. 1, 1952, pp. 38-44.

135. "On Vitamins in Sewage Sludge, II. Formation of Vitamin B12—Folic Acid—and Folinic Acid Factors in Municipal Sludge," by H. Y. Neuyahr, Acta Chemica Scandinovica, Vol. 9, 1955, pp. 622-630.

136. "On Vitamins in Sewage Sludge III. Vitamin B_{12} Activity of Different Types of Sewage Sludge," by H. J. Neujahr, Acta Chemica Scandinavica, Vol. 9, 1955, pp. 803-806.

137. "On Vitamin B_{12} Factors in Sewage Sludge," by H. Y. Neujahr, Almqvist and Wiksells Boktryckeri A B, Uppsala, Sweden, 1960 (thesis).

138. "Biochemical Geography; Some Aspects of Recent Vitamin Research," by S. H. Hutner, L. Provasoli, J. J. A. McLaughlin, and I. J. Pintner, Geographical Review, Vol. 46, No. 3, pp. 404-407.

139. "The Production of Vitamin B_{12}—Active Substances by Marine Bacteria," by T. J. Starr, M. E. Jones, and D. Martinez, Limnology and Oceanography, Vol. 2, No. 2, 1957, pp. 114-119.

140. "A Method for the Measurement of Vitamin B_{12} Concentration in Sea Water," by K. W. Daisley, Journal, Marine Biological Association, United Kingdom, Vol. 37, 1958, pp. 673-681.

141. "Vitamin B_{12} in Sea Water," by K. W. Daisley, Preprints, International Oceanographic Congress, American Association for the Advancement of Science, 1959, pp. 914-915.

142. "A Preliminary Investigation of the Variation of Vitamin B_{12} in Oceanic and Coastal Waters," by C. B. Cowey, Journal, Marine Biological Association, United Kingdom, Vol. 35, 1956, pp. 609-620.

143. "Studies on Vitamin B_{12} in Sea Water-II," by K. Kashiwada, D. Kakimot, T. Merita, A. Kanazawa, and K. Kawagoe, Bulletin, Japanese Society of Scientific Fisheries, Vol. 22, No. 10, 1957, pp. 637-640.

144. "Vertical Distribution of Vitamin B_{12} in the Sea," by K. W. Daisley and L. R. Fisher, Journal, Marine Biological Association, United Kingdom, Vol. 37, 1958, pp. 683-686.

145. "Studies on Vitamin B_{12} in Sea Water," by K. Kashiwada, D. Kakimot, and A. Kanzawa, Preprints, International Oceanographic Congress, American Association for the Advancement of Science, 1959, pp. 924-925.

146. "Vitamin B_{12} in Suspended Solids and Marsh Muds Collected along the Coast of Georgia," by P. R. Burkholder and L. M. Burkholder, Limnology and Oceanography, Vol. 1, No. 3, 1956, pp. 202-208.

147. "Preliminary Observations on Cobalt and Vitamin B_{12} in Fresh Water," by R. J. Benoit, Limnology and Oceanography, Vol. 2, No. 3, 1957, pp. 233-240.

148. Robbins, et al, Bull. Torrey Botanical Club, Vol. 77, 1950, pp. 423-441; Vol. 78, 1951, pp. 363-375. Summarized by Benoit (143).

149. "Relative Amounts of Vitamin B_{12} in Detritus from Oceanic and Estuarine Environments near Sapelo Island, Georgia," by T. J. Starr, Ecology, Vol. 34, No. 4, 1956, pp. 659-664.

150. "Uptake of Radioactive Cobalt and Vitamin B_{12} by some Marine Algae," by L. E. Ericson, Chemistry and Industry, 1952, pp. 829-830.

151. "Some Aspects of Cobalt Metabolism by Rhodymenia palmata with Particular Reference to Vitamin B_{12} Content," by R. Scott and L. E. Ericson, Journal of Experimental Botany, Vol. 6, No. 18, 1955, pp. 348-361.

152. "The Vitamin B_{12} Activity of Mullet and Shark Serum," by T. J. Starr, D. Martinez, and W. Fosberg, Limnology and Oceanography, Vol. 2, No. 2, 1957, pp. 111-113.

153. "Some Ecological Aspects of Vitamin B_{12} - active Substances," by T. J. Starr and F. Sanders, Texas Reports on Biology and Medicine, Vol. 17, No. 1, 1959, pp. 49-59.

154. "General Features of the Oceans," by R. H. Fleming, Geological Society of America, Memoir 67, Vol. 1, 1957, pp. 87-108.

155. "Allgemeine Meereskunde," by G. Dietrich and K. Kalle, Borntraeger, Berlin, 1957.

156. "The Relationship between Local Wind and Water Movement in Coastal Waters of the British Isles," by V. F. C. Veley, in Ref. 4.

157. "Inshore Circulation Patterns and Oceanic Disposal of Waste," by R. B. Tibby, in Ref. 4.

158. "Nearshore Circulation Systems," by D. L. Inman, in Ref. 4.

159. "The Gulf Stream," by H. Stommel, University of California Press, 1958.

160. "Marine Geology," by Ph. H. Kuenen, Wiley, 1950.

161. "The Sea Off Southern California," by K. O. Emery, Wiley, 1960.

162. "Oceanographic Observations in Santa Monica Bay, California, 1957," by C. G. Gunnerson, unpublished report in files of Bureau of Sanitation, City of Los Angeles, 1958.

163. "Environmental Factors Affecting the Vertical Temperature Structure of the Upper Layers of the Sea," by E. C. La Fond, Andhra University Memoirs in Oceanography, Waltair, India, 1954, pp. 93-100.

164. "Appendix to Progress Report Number 3, Oceanographic Investigation of Santa Monica Bay," Bureau of Sanitation, City of Los Angeles, 1956 (mimeo).

165. "Recent Increases in Coastal Water Temperature and Sea Level—California to Alaska," by H. B. Stewart, Jr., B. D. Zetler, and C. B. Taylor, USC & GS Technical Bulletin No. 3, 1958.

166. "Progress Report, California Cooperative Oceanic Fisheries Investigation, 1 July 1956 - 1 January 1958," California Department of Fish and Game Laboratories, Terminal Island, California, 1958.

167. "Physical and Chemical Characteristics of the Water over the Southern California Shelf, 1956-58," by R. B. Tibby and R. D. Terry, in Oceanographic Survey of the Contenental Shelf Area of Southern California, Publication No. 20, State Water Pollution Control Board, Sacramento, California, 1959, pp. 111-168.

168. "An Analysis of Stirring and Mixing Processes in Incompressible Fluids," by C. Eckart, Journal of Marine Research, Vol. 7, No. 3, 1948, pp. 265-275.

169. "Note on Eddy Diffusion in the Sea," by L. F. Richardson and H. Stommel, Journal of Meterology, Vol. 5, 1948, pp. 238-240.

170. "Horizontal Diffusion Due to Oceanic Turbulence," by H. Stommel, Journal of Marine Research, Vol. 8, No. 3, 1949, pp. 199-225.

171. "Diffusion in Bikini Lagoon," by W. H. Munk, G. C. Ewing, and R. R. Revelle, Transactions, American Geophysical Union, Vol. 30, No. 1, pp. 59-66.

172. "The Application of Turbulence Theory to Oceanography," by E. Inoue, (in Japanese), Journal, Meteorological Society of Japan, Vol. 28, No. 11, 1950.

173. "Horizontal Diffusion in the Sea," by J. Joseph and H. Sender, Deutsche Hydrographische Zeitschrift, Vol. 2, No. 2, 1958, pp. 49-77.

174. "Eddy Diffusion in Homogeneous Turbulence," by G. T. Orlob, Proceedings, ASCE, Vol. 85, No. HY 9, 1959, pp. 75-101.

175. "Horizontal Diffusion," by F. C. W. Olson and T. Ichiye, Science, Vol. 130, No. 3384, 1959, p. 1255.

176. "Discussion of Eddy Diffusion in Homogeneous Turbulence," by T. Ichiye Proceedings, ASCE, Vol. 86, No. HY 4, 1960, pp. 97-101.

177. "The Dispersal of Effluent in the Sea, by J. Wright, Atomic, August 1946, pp. 274-279.

178. "Diffusion of Sewage Effluent in an Ocean Current, by N. H. Brooks, in Ref. 4.

179. "Radioactive Waste Disposal into Atlantic and Gulf Coastal Waters," by D. E. Carritt, et al, National Academy of Science-National Research Council Publication No. 655, 1959.

180. "Discussion of Eddy Diffusion in Homogeneous Turbulence," by C. G. Gunnerson, Proceedings, ASCE, Vol. 85, No. HY 4, 1960, pp. 101-109.

181. "A Study of Mixing Processes over the Edge of the Continental Shelf," by A. R. Miller, Journal of Marine Research, Vol. 9, No. 12, 1950, pp. 145-160.

182. "Contraction on Mixing of Sea Waters," by N. N. Zobov and K. D. Sabinin, Preprints, International Oceanographic Conference, American Association for the Advancement of Science, 1959, pp. 808-809.

183. "60 Percent of Population Served by 40 California Ocean Outfall Sewers," by F. D. Bowlus, Western City, Vol. 31, No. 4, 1955, pp. 42-44.

184. "Water Quality and Upwelling at Gray's Harbor Entrance," by E. A. Pearson and G. A. Holt, Limnology and Oceanography, Vol. 5, No. 1, 1960, pp. 48-56.

185. "Shoreward Upslope of the Layer of Minimum Oxygen off Bombay: Its Influence on Marine Biology, Especially Fisheries," by J. N. Carruthers, S. S. Gogate, J. R. Naidu and T. Laevastu, Nature, Vol. 183, 1959, pp. 1084-1087.

186. "An Oceanographic Study between the Points of Trinidad Head and the Eel River," by G. H. Allen, et al, 1959 Annual Report for the State of California Water Pollution Control Board, Humboldt State College, Arcata, California, 1959.

187. "Some Oceanographic Applications of Recent Determinations of the Solubility of Oxygen in Sea Water," by F. A. Richards and N. Corwin, Limnology and Oceanography, Vol. 1, No. 4, 1956, pp. 263-267.

188. "A Treatise on Limnology, Volume 1: Geography, Physics, and Chemistry," by G. E. Hutchinson, Wiley, 1957.

189. "Transparency in Santa Monica Bay Water," by C. E. Imel, MS Thesis, School of Engineering, University of Southern California, 1960.

190. "Transparency of Water Off Southern California," by K. O. Emery, Transactions, American Geophysical Union, Vol. 35, 1954, pp. 217-220.

191. "Chemistry of Sedimentation," by U. G. Whitehouse, in Study of Nearshore Recent Sediments and Their Environments, Apl Research Project 51, Reference 52-51, Scripps Institution of Oceanography, 1952, pp. 23-32.

192. "Chemistry of Sedimentation," by U. G. Whitehouse and L. M. Jeffrey, Reference 53-43, Scripps Institution of Oceanography, 1953, pp. 31-38.

193. "Diagenetic Modification of Clay Mineral Types in Artificial Sea Water," by U. G. Whitehouse and R. S. McCarter, in Clays and Clay Minerals, National Academy of Sciences-National Research Council, Washington, D. C., Publication 566-1958, pp. 81-119.

194. "Differential Settling Tendencies of Clay Minerals in Saline Waters," by U. G. Whitehouse, L. M. Jeffrey, and J. D. Debbrecht, in Proceedings of the Seventh National Conference on Clays and Clay Minerals, Pergamon Press, 1960, pp. 1-79.

195. "Discussion of the Settling Properties of Suspensions," by C. G. Gunnerson, Proceedings, ASCE, Journal of Hydraulics, in press.

196. "Adsorption of ABS on Particulate Materials in Water," by C. E. Renn and M. F. Brada, Sewage and Industrial Wastes, Vol. 31, No. 7, 1959, pp. 850-854.

197. "Slicks, Surface Films, and Internal Waves," by G. Ewing, Journal of Marine Research, Vol. 9, No. 3, 1950, pp. 161-187.

198. "Slicks and Temperature Structure in the Sea," by E. C. La Fond, Research Report 937, U. S. Navy Electronics Laboratory, San Diego, California, 1959.

199. "Cruise Reports of Offshore Survey, 8/6/58 and 10/18/58," by C. G. Gunnerson, reports in files of Bureau of Sanitation, City of Los Angeles, 1958.

200. "Uber interne Gezeitenwellen and ihre Stabilitatsbedingungen," by A. Defant, Arch. Met. Geophys. Bioklim., (A), Vol. 1, No. 1, 1948, pp. 39-61.

201. "Appendix to Cruises for an Oceanographic Survey of Santa Monica Bay, California," by R. E. Stevenson, Allan Hancock Foundation, University of Southern California, Los Angeles, 1957 (multilith).

202. "Reality and Illusion in Oceanographic Surveys," by A. Defant, Journal of Marine Research, Vol. 9, No. 2, 1950, pp. 120-138.

203. "Estuarine Hydrography," by D. W. Pritchard, Advances in Geophysics, Vol. I, Academic Press, 1952, pp. 243-280.

204. "Estuaries and Lagoons, I. Physical and Chemical Characteristics," by K. O. Emery and R. E. Stevenson, Memoir 67, Vol. 1, Geological Society of America, 1957, pp. 673-693.

205. "Estuaries and Lagoons, II. Biological Aspects," by J. W. Hedgepeth, Memoir 67, Vol. 1, Geological Society of America, 1957, pp. 694-750.

206. "Oxygen Balance of an Estuary," by D. J. O'Connor, Proceedings, ASCE, Vol. 86, No. SA3, 1960, pp. 35-55.

207. "Operating Characteristics of an Oceanographic Model of Puget Sound," by Maurice Rattray, Jr. and J. H. Lincoln, Transactions, American Geophysical Union, Vol. 36, No. 82, 1955, pp. 251-261.

208. "An Oceanographic Model of Puget Sound," by C. A. Barnes, J. H. Lincoln, and M. Rattray, Jr. Proceedings of the Eighth Pacific Science Congress, Vol. III, 1957, pp. 686-704.

209. "Diffusion in a Sectionally Homogeneous Estuary," by R. Kent, Proceedings, American Society of Civil Engineers, Vol. 86, No. SA2, 1960, pp. 15-47.

210. "Application and Limitations of Estuary Models in Pollution Analyses," by H. B. Simmons, in Ref. 4.

211. "Significance of Bottom Topography," by J. S. Creager, in Ref. 5.

212. "Transportation of Collidal Sediment in the Freshwater-Marine Transition Zone," by Bruce W. Nelson, Preprints, International Oceanographic Congress, American Association for the Advancement of Science, 1959, pp. 640-641.

213. "Oceanography and Prediction of Pulp Mill Pollution in Alberni Inlet," by J. P. Tully, Bulletin No. 83, Fisheries Research Board of Canada, 1949.

214. "Pulp Mill Pollution in Alberni Harbor, British Columbia," by M. Waldichuk, Sewage and Industrial Wastes, Vol. 28, No. 2, 1956, pp. 199-205.

215. "Computation of Pollution in the Yaquina River Estuary," by W. V. Burt and L. D. Marriage, Sewage and Industrial Wastes, Vol. 29, No. 12, 1957, pp. 1385-1389.

216. "Hydrography of a Positive, Shallow, Tidal Bar-built Estuary (Report on the Hydrography of the Polluted Area of Biscayne Bay)," by Ilmo Hela, C. A. Carpenter, Jr., and J. K. McNulty, Bulletin of Marine Science of the Gulf and Caribbean, Vol. 7, No. 1, 1957, pp. 47-99.

217. "Bay Fills and Bulkhead Lines," by P. Brunn, Engineering Progress at the University of Florida, Vol. 13, No. 3, University of Florida, Gainesville, 1959, pp. 1-16.

218. "Bayfill and Bulkhead Line Problems—Engineering and Management Considerations," by P. Bruun and J. M. DeGrove, Studies in Public Administration Number 18, University of Florida Public Administration Clearing Service, Gainesville, Florida, 1959.

219. "Pollution of Los Angeles and Long Beach Harbors," by L. C. Larson, Proceedings ASCE, Vol. 82, No. SAI, Paper 891, 1956, pp. 1-10.

220. "Pitting Corrosion of Reserve Fleet Ships," by E. F. Corcoran and J. S. Kittredge, paper presented at Conference on Marine Corrosion and Fouling Problems, Scripps Institution of Oceanography, April 18-20, 1956.

221. "Salt Budget in the Lake Washington Ship Canal System," by Maurice Rattray, Jr., G. R. Seckel, and C. A. Barnes, Journal of Marine Research, Vol. 13, No. 3, 1954, pp. 263-275.

222. "Ocean Outfall Design," by Hyperion Engineers, a Joint Venture, 828 South Figueroa Street, Los Angeles 17, California, 1957.

223. "Two Long Ocean Outfalls Constructed," by D. L. Narver, Jr. and E. H. Graham, Jr., Civil Engineering, Vol. 28, No. 1, 1958, pp. 6-11.

224. "Engineering Goes to Sea," by D. R. Miller, Public Works, Vol. 91, No. 10, 1956, pp. 136-137.

225. "Operation of a 7-mile Digested Sludge Outfall," by N. B. Hume, R. D. Bargman, C. G. Gunnerson, and C. E. Imel, Proceedings, ASCE, Vol. 85, No. SA4, 1959, pp. 71-87.

226. "Report on Marine Investigations for the Submarine Aqueduct for Margarita and Coche, Report to Instituto Nacional de Obras Sanitarias, Caracas," by Daniel, Mann, Johnson, and Mendenhall de Venezuela, C. A., 1958.

227. "Pipeline Is Pulled 19 Miles on Sea Bottom," Engineering News-Record, Vol. 164, No. 10, 1960, pp. 38-40.

228. "Corrosion Protection Features of the Hyperion Outfall," by H. J. Keeling, Corrosion, Vol. 15, No. 7, 1959, pp. 41-46.

229. "Resistance of Organic Materials and Cable Structures to Marine Biological Attack," by L. R. Snoke, The Bell System Technical Journal, Vol. 36, No. 5, 1957, pp. 1095-1127.

230. "Rubber Pipe Used in Underwater Waste Disposal," Public Works, Vol. 91, No. 1, 1960, p. 152.

231. "The Empirical Approach for Determining the Length of an Ocean Outfall," by R. Pomeroy, in Ref. 4.

232. "Diffusers for Disposal of Sewage in Sea Water," by AM Rawn, F. R. Bowerman, and N. H. Brooks, Proceedings, American Society of Civil Engineers, Vol. 86, No. SA2, 1960, pp. 65-105.

233. "The Effects of Atomic Radiation on Oceanography and Fisheries," by Roger Revelle, et al, Pub. No. 551, National Academy of Sciences—National Research Council, 1957.

234. "Radioactive Waste Disposal from Nuclear-Powered Ships," by D. W. Pritchard, et al, Pub. No. 658, National Academy of Sciences—National Research Council, 1959.

235. "Radioactive Tracer Study of Sewage Field in Santa Monica Bay," by R. L. Ely, Jr., IRE Transactions on Nuclear Science, NS-4, March, 1957, pp. 49-50.

236. "Selection and Handling of a Radio Tracer for Studying Sewage Distribution," by E. I. Goodman, Industrial and Engineering Chemistry, Vol. 50, No. 2, 1958, pp. 210-211.

237. "Rate of Dispersion in the Wake of a Barge at Sea," by B. H. Ketchum and W. L. Ford, Transactions, American Geophysical Union, Vol. 33, No. 5, 1952, pp. 680-684.

238. "A Study of Chemical Waste Disposal at Sea," by A. C. Redfield and L. A. Walford, Pub. 201, National Academy of Sciences—National Research Council, 1951.

239. "Disposal of Wastes at Sea," by J. W. Eberman, Sewage and Industrial Wastes, Vol. 28, No. 11, 1956, pp. 1365-1370.

240. "Deep Sea Disposal of Industrial Wastes," by D. W. Hood, B. Stevenson, and L. M. Jeffrey, Industrial and Engineering Chemistry, Vol. 50, No. 6, 1958, pp. 885-888.

241. "The Spreading of Sinking Particles in the Sea," by F. Beyer, Sewage and Industrial Wastes, Vol. 27, No. 9, 1955, pp. 1073-1078.

242. "Quantity of Oily Substances on Beaches and in Nearshore Waters," by R. C. Merz, Part I. Publication No. 21, State of California Water Pollution Control Board, Sacramento, California, 1959.

243. "Characterization of Coastal Oil Pollution by Submarine Seeps," by A. A. Rosen, L. R. Musgrave, and J. J. Lichtenberg, Part 2, Publication No. 21, State of California Water Pollution Control Board, Sacramento, California, 1959.

244. Personal communication from D. W. Pritchard, 1960.

245. "Ecological Effects of Sewage in Biscayne Bay: Distribution of Coliform Bacteria, Chemical Nutrients and Plankton Volumes," by J. K. McNulty, E. S. Reynolds, and S. M. Miller, in ref. 3.

246. "An Oceanographic Investigation of Conditions in the Vicinity of Whites Point and Hyperion Sewage Outfalls, Los Angeles, California," Report to Citizens Committee on Sewerage Problems by Staff, Scripps Institution of Oceanography, May, 1954 (ms).

247. "The Oceanography of Santa Monica Bay, California," by R. E. Stevenson, R. B. Tibby, and D. S. Gorsline, Allan Hancock Foundation, University of Southern California, Los Angeles, California, 1956 (multilith).

248. "Plankton and Associated Nutrients in the Waters Surrounding Three Sewer Outfalls in Southern California," by R. E. Stevenson and J. R. Grady, Allan Hancock Foundation, University of Southern California, Los Angeles, California, 1956 (multilith).

249. "Submarine Geology of Santa Monica Bay, California," by R. D. Terry, S. A. Keesling, and E. Uchupi, Allan Hancock Foundation, University of Southern California, 1956.

250. "State Water Pollution Control Board Decision on Hyperion Discharge Requirements (May 2, 1956) and Regional Water Pollution Control Board 56-43 and 58-67. Order," by State of California Regional Water Pollution Control Board No. 4, Los Angeles, California, 1959.

251. "Receiving Water Analyses," by W. F. Garber, in ref. 4.

252. "Nearshore Ocean Currents off San Diego, California," by R. D. Gaul and H. B. Stewart, Jr., Journal of Geophysical Research, Vol. 65, No. 5, 1960, pp. 1543-1556.

253. "Travel of Pollution in Shoreline Coastal Waters," by I. Nusbaum, H. E. Miller, and A. W. Reinhardt, Proceedings, ASCE, Vol. 81, Paper No. 781, 1955.

254. "Sanitary Engineering and Oceanography in Santa Monica Bay, California," by C. G. Gunnerson, paper presented at Annual Meeting, Pacific Section, American Society of Limnology and Oceanography, Logan, Utah, 1958.

255. "Oceanographic Survey of the Continental Shelf Area of Southern California," Publication No. 20, State Water Pollution Control Board, Sacramento, California, 1959.

256. "Summary of Marine Waste Disposal Research Program in California, 1960," by E. A. Pearson, J. E. McKee, and R. Pomeroy, State Water Pollution Control Board, Sacramento, California, in press.

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STORM WATER AND COMBINED SEWAGE OVERFLOWS[a]

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SYNOPSIS

Most of the Larger and older cities in the United States are served by combined sewer systems. The intersection and treatment of the dry weather sewage and the first flushings of storm water has accomplished much toward pollution abatement. Treatment of overflows by retention and chlorination can improve the conditions in the receiving waterway, in some respects, at feasible costs.

FOREWORD

The present day interest in pollution abatement is the result of many changes and developments. Mark Hollis, F. ASCE has cited[3] some interesting figures. He stated that about 24 million people in the United States were served by sewer systems at the turn of the century. This figure increased to 47 million by 1920, to 70 million by 1940, and as of 1960, is approximately 105 million. He estimated that 200 million would be served by 1980. Both increased population and the concentration of population in urban and suburban developments have resulted in this rapid increase. The volumes of industrial waste waters have increased to an even greater degree and the future must anticipate continued increases in amount of waste for disposal.

The characteristics of both human and industrial wastes have changed materially, since the turn of the century, with the use of synthetic detergents and with chemical and other industries contributing complex wastes with resulting problems to known treatment processes.

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[3] Presented before the Am. Water Works Assn., May, 1960.

Great progress has been made in the treatment of domestic and industrial wastes, but this progress has hardly kept up with increasing needs. There is serious doubt as to whether our waterways are in as good condition, overall, in 1960 as they were at the turn of the century. Much remains to be done to conserve our water resources in order to meet our future needs for water-supply purposes and to preserve them for recreational uses.

Any program for pollution abatement must recognize all significant sources of pollution and contamination. Not the least, in this regard, is the pollution introduced into a waterway through overflows from combined sewers. This source has been accented by an increasing use of waterways for recreation, particularly swimming and boating, which require, by their nature of human contact, a special standard of water cleanliness.

In most of the older cities, and particularly the larger cities, by far the greater part of the sewers were designed and built and are operated as combined sewers. Even with the best and most complete provision for sewage treatment, these systems contribute directly to the pollution of the waterways through overflows during storms. The control of this source of pollution is the subject of this presentation.

DEFINITIONS

Some definitions relating to this problem may be pertinent and helpful.

Sanitary sewers comprise a system of pipes and conduits receiving only water borne wastes from residences, commercial buildings, and industrial plants.

Storm sewers comprise a system of pipes and conduits receiving only surface runoff from roofs, paved areas, and other surfaces resulting from rainstorms.

Combined sewers receive both water-borne wastes and surface runoff from storms.

Intercepting sewers comprise a system of pipes and conduits to collect water-borne wastes and to convey them to a proper location for treatment and disposal.

Combined sewage overflows are the direct discharges to a waterway of the flows of mingled water-borne wastes and storm water in excess of the amounts intercepted for treatment.

Sewage treatment is the process of removing polluting material from sewage and industrial waste to condition it for discharge to the receiving waterway. The extent of treatment is customarily related to the assimilation capacity of the waterway and the desired characteristics of the waterway and its use.

Receiving waterways are the recipients of the effluent from sewage-treatment works and may be a stream or river, a fresh-water lake, or the ocean or estuarial bay or harbor.

HISTORICAL

The concept of disposal of human waste by flowing water is indeed old, as is the removal and disposal of rainwater by means of ditches and pipe systems. There are records of such installations in ancient Greece and Rome. The idea of combining these functions into a common system was quite natural

when the purpose was only to remove these troublesome results of urban living from the immediate vicinity. The saving in cost was obvious and the future effects were not visualized. It would have taken great vision to have anticipated the problems that now face our great urban centers in the treatment of wastes and restoration and preservation of our water resources. The fact remains that combined sewers exist and that this poses an additional problem in pollution abatement.

SEWAGE TREATMENT

At about the turn of the century, the relationship between pollution and disease was recognized and the trend toward abatement was started. The Herculean cleanup project at Chicago, Ill. resulted in the elimination of all waste discharges from Lake Michigan by the construction of a system of diversion and intercepting sewers and the Sanitary and Ship Canal. The results of this effort are well known.

Pollution abatement by sewage treatment has been undertaken for several reasons including (1) to eliminate unsightly and obnoxious conditions in the waterway, (2) to protect a water supply, and (3) to restore a waterway to a condition suitable for recreational uses. The extent of treatment is related to the use of the receiving waterway and its ability to assimilate a pollution load. One objective, of course, is to accomplish the desired result with the least expenditure.

It was obviously impractical to plan and build intercepting and treatment works of capacity adequate to handle the maximum flows in combined sewers. In most cases, the elimination of the continuous discharge of untreated waste and, during periods of heavy flows resulting from storm runoff, of 1.5 to 2.0 times the average flow, has resulted in an over-all interception of 95% to 97% of the total pollution load which is considered to be acceptable both from the points of view of cost and practicability of operation. Most projects for treatment of wastes in combined sewer systems have been developed under a procedure approximating this general basic conception in which 3% to 5% of the total pollution load is discharged directly to the waterway, untreated, through combined sewage overflows.

USES OF WATERWAYS

As the extent of sewage treatment needed is related to the kind of receiving waters, the assimilation capacity and the use of the waterway, the effects of the pollution from the intermittent overflows from combined sewers must be considered. For example, a stream or lake used for water supply may receive a treated effluent if the chemical and bacterial characteristics are maintained in such condition as to be susceptible to water treatment. This may require chlorination and effective dispersion. The slugs of pollution from overflows, when 95% or more of the sewage is discharged without treatment, are likely to be controlling. Where the waterway is used for swimming and boating, the chlorination of the treatment-plant effluent may provide adequate protection most of the time. Storm overflows of combined sewage may introduce slugs of bacterial pollution to such an extent as to preclude such uses over considerable periods.

Fish life can be maintained in a waterway only with an adequate supply of dissolved oxygen. If fishing is a desired and proper use of the waterway, treat-

ment must be such as to provide the necessary oxygen at all times. In a case where complete treatment accomplishes a continuous reduction of 90% in B.O.D., overflows from combined sewers may introduce slugs of B.O.D. containing as much as 97% of that in the raw sewage. As a result, the total B.O.D. load on the waterway, including that from the overflows, will be approximately 30% more than that from the treatment plant effluent.

It is obvious that, even with complete treatment of dry-weather wastes, the pollution discharged intermittently through storm water overflows can seriously impair the usefulness of the waterway.

OVERFLOW CONTROL BY INTERCEPTOR CAPACITY

Jack E. McKee, F. ASCE has presented,[4] an analysis of the relationship of interceptor capacity to the amount of sanitary sewage lost through overflows and the frequency of such overflows. His conclusions are summarized in

TABLE 1

Ratio of Int. Capacity to Dry Weather Flow (1)	Per Cent of Sewage lost (2)	Number of Overflows per month (3)	Average Interval Days (4)
2	2.6	5.5	5.5
3	1.9	5	6
4	1.5	4.5	6.7
5	1.2	4.0	7.5
10	0.5	3.1	9.7
20	0.2	2.1	14.3
50	0.1	0.8	37.0

Table 1. In order to reduce the discharge of sewage through overflows by 50%, that is, from 2.6% to 1.2% of the total sewage quantity, it would be necessary to provide 2-1/2 times the capacity in intercepting sewers that would be provided in the more concentional design of twice the dry-weather flow. Even this increased capacity would reduce the number of overflows only to 4 per month from 5.5 per month and would increase the average interval between overflows from 5.5 days to 7.5 days. When it is considered that treatment plant structures would have to be increased to handle the increased intercepted quantity or, if not, that the increased quantity would be discharged to the waterway bypassed at the plant site without treatment, the increased capacity and cost of intercepting sewers would result in little, if any, over-all advantage.

OVERFLOW CONTROL BY SEPARATION

The overflow of combined sewage can, of course, be eliminated by providing separate systems of sewers. This procedure has been adopted in many cities for newly developed areas, and some state controlling bodies require such systems. However, it is very difficult to contemplate the construction of a new

[4] Presented before the Boston Soc. of Civ. Engrgs., March, 1947.

system of sanitary sewers in the densely populated areas of the older cities. Estimates of cost have been made for the District of Columbia, indicating a total cost of about $214,000,000 for 11,740 acres, or an average cost of about $18,000 per acre. In Chicago, it has been estimated that separation would cost in excess of $2,250,000,000 for 135,000 acres, or an average of about $17,000 per acre. Even these costs do not fully recognize the great inconvenience to property and traffic that would result, nor the long period of time involved.

In the District of Columbia, the principle of separation has been adopted and a schedule of the operation has been made. Under an active program, this schedule calls for completion of separation in about a third of the area now served by combined sewers by the year 2000.

OVERFLOW TREATMENT

The treatment of storm-water and combined-sewage overflows presents many problems of cost as well as of methods related to objectives. In a large, old and congested city, the overflow outlets are likely to be located where areas are unavailable for treatment installations. The transportation of the overflow quantities to an available site can be very costly. The feasibility of overflow treatment is therefore largely related to the cost and availability of sites for treatment works.

Any consideration of treatment of storm-water and combined-sewage overflows must be related to the needs of the waterway and its desired use. It is accepted that a conventionally-designed system of intercepting sewers should take the dry-weather flow and the first flushings of storm flow. This often results in a capacity for about twice the dry-weather flow, which will result in the discharge, through overflows, of about 3% of the sewage without treatment. Complete treatment of the intercepted flow can be expected to accomplish an average reduction in the dry weather pollution load of about 90% ,or about 87.3% of the total load. Even if complete treatment of overflows was possible, which is not the case because of the intermittent occurrences and wide range of flow rates, the best that could be accomplished is an over-all average of 90% removal, an increase of less than 3%. The need of a waterway for pollution abatement cannot be defined so closely for over-all treatment.

The potential benefits of overflow treatment are obviously in reducing the effects of slugs of pollution during heavy storms when, for a relatively short period of time, as much as 95% of the sewage is discharged to the waterway through overflows and without treatment. The effects on the waterway of the discharge of B.O.D. and solids are not immediate. Their effects are related to time, so the intermittent discharges approach an increase in an average load.

The discharge, through overflows, of slugs of unsightly floating solids and bacterial pollution have an immediate effect on the usefulness of the waterway for recreational purposes. Overflow treatment by retention to contain floating solids and by chlorination to kill bacteria can attain significant benefits.

THE NEW YORK CITY PROBLEM

The program for sewage treatment in New York, N.Y. is well advanced, with nine major treatment plants accomplishing reductions in pollution of from 60% to over 90% ,from about 800 mgd. of average sewage flow. In some locations, the effluent is chlorinated in the summer months. In spite of this, the

waters of Jamaica Bay and the upper East River near Long Island Sound are not continuously suitable for recreational uses. Additional bathing beaches are considered necessary by the Park Department. Studies have been made to determine the sources of bacterial pollution and the remedial measures necessary to permit the establishment and continuous use of bathing beaches in these areas.

Records of bacterial analyses of samples taken at the proposed beach locations and elsewhere showed a definite relationship between high bacterial counts and storm overflows. The control of bacterial pollution from this marginal source appeared necessary if the waters were to be made safe for bathing.

Studies were made to determine the locations of all outlets to the waterway discharging combined overflows, the areas served and the sources of sewage and storm runoff. The investigation revealed a number of abuses in the operation of the sewer systems, including the following:

1. Sewer systems in some areas, designed and intended to serve as separate sanitary sewers, were receiving considerable quantities of surface runoff.
2. Some storm outlet relief sewers were receiving overflows from sanitary trunk sewers.
3. Some intercepting sewers were receiving direct surface drainage.
4. Some combined sewers were obtaining capacity relief by overflows to separate storm outlets.

In some cases, adjustments to the sewer systems, to reduce the amount of overflow requiring treatment, were found to be feasible, and were recommended.

In the absence of any actual local records of the frequency, duration, and quantities of overflows, a rational approach relating rainfall to sewage quantities and tributary areas was undertaken.

Hourly records of rainfall for the five summer months, May to September, and over the 8-yr period from 1950 to 1957 were obtained for the nearby station of the United States Weather Bureau at LaGuardia Airfield. These were tabulated and analyzed to establish such relationships as (1) number of storms, (2) total rainfall in the storm, and (3) duration of the storm. It was found that an average of forty rainstorms could be expected in the five summer months. This is an average interval between storms of about 3.8 days. The relationship between the total rainfall in a storm and the percentage of the storms in which the amount is exceeded is shown in Fig. 1. The relationship between the total rainfall in a storm and its probable duration is shown in Fig. 2, which, as for Fig. 1 are from LaGuardia Field weather bureau records for May through Sept., 1941 through 1947. This study was used to estimate the probable number of storms, the total amount of rainfall and the probable duration of each of the rainstorms that can be expected in the 5-month period of a year extending from May through September. This data is shown in Table 2.

In translating these data into a rational analysis of the amount, the number and frequency of overflows, and the characteristics of the discharges, several basic factors were estimated and used, including the following:

1. The average dry weather sewage quantity is 6,530 gal per acre per day or 872 cu ft per 24 hr per acre.
2. All flows of less than twice the average sewage quantity are intercepted and treated at the sewage treatment plant.

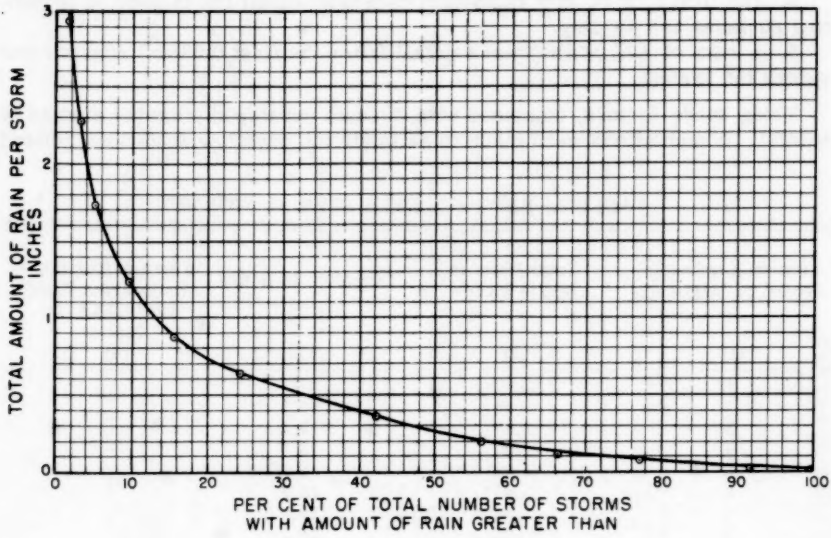


FIG. 1.—RAINFALL IN A STORM

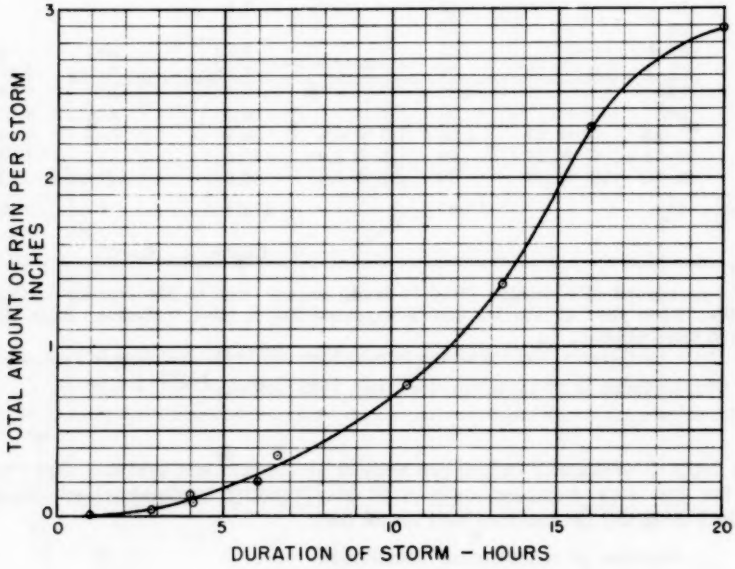


FIG. 2.—RAINFALL AND DURATION

3. The first 0.03 in. of a rainstorm causes no runoff but is used up in wetting surfaces and ponding.

4. A sum of 40% of the total rainfall (after the first 0.03 in.) runs off and enters the system.

Using these factors, combined with the data developed from the studies of rainfall, computations were made to estimate the overflow conditions related

TABLE 2.—RAINFALL DATA TYPICAL STORMS[a]

Storm Number In Order Of Magnitude (1)		Total Rain, In Storm Inches (2)		Duration, In Hours (3)	Average Rainfall At La Guardia Field[b] 1941-1957, In Inches (4)	
1		2.50		17.0		
2		1.80		14.7		
3		1.40		13.5		
4		1.20		12.7		
55		1.05		12.0		
6		.90		11.3		
7		.80		10.7		
8		.73		10.3		
9		.67		9.8		
10		.62		9.5		
11		.58		9.2		
12		.54		8.9		
13		.50		8.6		
14		.46		8.3		
15		.42		7.9		
16		.38		7.5		
17		.35		7.2	May	3.88 in.
18		.32		6.9	June	2.80
19		.29		6.5	July	3.78
20		.26		6.2	Aug.	5.21[c]
21-25	5 @ .20	1.00	5 @ 6.0	30.0	Sept.	3.08
26-30	5 @ .12	.60	5 @ 4.0	20.0		18.75
31-40	10 @ .06	.60	10 @ 3.0	30.0	Adjust.-	0.72[c]
Total 40		17.97		278.7		18.03

Check

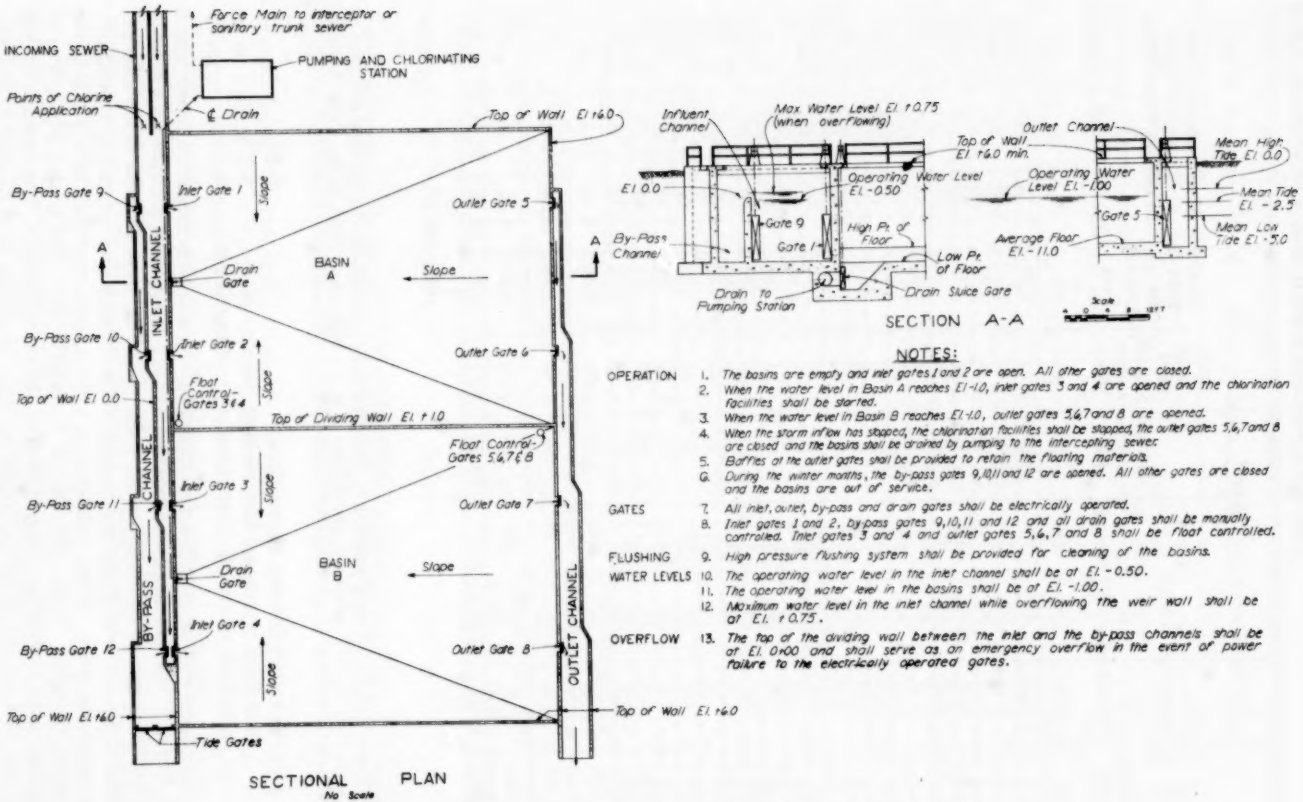
[a] 8 yr record of 5 months (May to Sept.) shows total of 324 storms during the 40 months. Each year 40 storms can be expected May to Sept. inclusive. Each storm is 2.5% of total number.

[b] From La Guardia Field Weather Bureau Records 1941-1947 May to Sept. inclusive.

[c] This includes 12.20 in. in hurrican Aug. 1955 Adjust. $\frac{12.20}{17}$ = 0.72 in.

to a typical area of 1,000 acres served by a combined system. The results, all for the five summer months of May through September, are shown on Table 3 and may be summarized as follows:

Number of rainstorms considered	40
Number of rainstorms causing overflows	25
Average interval between overflows	6 days
Total time of overflows	229 hrs



NOTES:

OPERATION
1. The basins are empty and inlet gates 1 and 2 are open. All other gates are closed.
2. When the water level in Basin A reaches El -1.0, inlet gates 3 and 4 are opened and the chlorination facilities shall be started.
3. When the water level in Basin B reaches El -1.0, outlet gates 5,6,7 and 8 are opened.
4. When the storm inflow has stopped, the chlorination facilities shall be stopped, the outlet gates 5,6,7 and 8 are closed and the basins shall be drained by pumping to the intercepting sewer.
5. Baffles at the outlet gates shall be provided to retain the floating materials.
6. During the winter months, the by-pass gates 9,10,11 and 12 are opened. All other gates are closed and the basins are out of service.

GATES
7. All inlet, outlet, by-pass and drain gates shall be electrically operated.
8. Inlet gates 1 and 2, by-pass gates 9,10,11 and 12 and all drain gates shall be manually controlled. Inlet gates 3 and 4 and outlet gates 5,6,7 and 8 shall be float controlled.

FLUSHING
9. High pressure flushing system shall be provided for cleaning of the basins.

WATER LEVELS
10. The operating water level in the inlet channel shall be at El. - 0.50.
11. The operating water level in the basins shall be at El. -1.00.
12. Maximum water level in the inlet channel while overflowing the weir wall shall be at El. +0.75.

OVERFLOW
13. The top of the dividing wall between the inlet and the by-pass channels shall be at El. 0.00 and shall serve as an emergency overflow in the event of power failure to the electrically operated gates.

FIG. 3.—STORM WATER TREATMENT PLANT TYPICAL DETAILS

TABLE 3.—STORM WATER TREATMENT BASIN FOR A

Storm No.	Duration In Hours	Total Rain, In Inches	Runoff		Sanitary Flow Million Cubic Feet	Total Flow Million Cubic Feet	To Treatment Plant (2 x Sanitary Flow) In Million Cubic Feet		
			Inches	Million Cubic Feet			Total	Runoff	Sanitary
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
1	17.0	2.50	.988	3.59	.62	4.21	1.24	1.06	.18
2	14.7	1.80	.708	2.57	.53	3.10	1.06	.88	.18
3	13.5	1.40	.548	1.99	.49	2.48	.98	.79	.19
4	12.7	1.20	.468	1.70	.46	2.16	.92	.72	.20
5	12.0	1.05	.408	1.48	.44	1.92	.88	.68	.20
6	11.3	.90	.348	1.27	.41	1.68	.82	.62	.20
7	10.7	.80	.308	1.12	.39	1.51	.78	.58	.20
8	10.3	.73	.280	1.02	.37	1.39	.74	.54	.20
9	9.8	.67	.256	.93	.36	1.29	.72	.52	.20
10	9.5	.62	.236	.86	.34	1.20	.68	.49	.19
11	9.2	.58	.220	.80	.33	1.13	.66	.47	.19
12	8.9	.54	.204	.74	.32	1.06	.64	.45	.19
13	8.6	.50	.188	.68	.31	.99	.62	.43	.19
14	8.3	.46	.172	.63	.30	.93	.60	.41	.19
15	7.9	.42	.156	.57	.29	.86	.58	.38	.20
16	7.5	.38	.140	.51	.27	.78	.54	.35	.19
17	7.2	.35	.128	.47	.26	.73	.52	.33	.19
18	6.9	.32	.116	.42	.25	.67	.50	.31	.19
19	6.5	.29	.104	.37	.24	.61	.48	.29	.19
20	6.2	.26	.092	.33	.23	.56	.46	.27	.19
21-25	5 @ 6.0 30.0	5 @ 2.0 1.00	.340	1.23	1.09	2.32	2.18	1.15	1.03
26-30	5 @ 4.0 20.0	5 @ .12 .60	.180	.65	.73	1.38	1.38	.665	.73
31-40	10 @ 3.0 30.0	10@ .06 .60	.120	.44	1.09	1.53	1.53	.44	1.09
Total	278.7	17.97	6.71	24.37	10.12	34.49	19.51	12.81	6.70
							↑	↑	
							100%	—56.6%	

[a] First 0.03 in. of each rainfall is deducted as an allowance for ponding and surface gal/acre/day = 0.872 mill cu ft per 24 hr. 1 in. Runoff = 3.63 mill cu ft. Total Sanitary

Per cent of time of overflows	6.2%
Per cent of sewage lost through overflows	2.6%
Per cent of runoff intercepted to treatment plant	52.5%

The objectives of overflow treatment can be met by a retention basin which will prevent the discharge of floating sewage solids and provide an adequate contact time for disinfection with chlorine. The first relates to the general design of the structure and the second to its volume and operating procedure. Computations were made, relating the anticipated overflows to various basin volumes, ranging from 200,000 to 1,200,000 cu ft for each 1,000 acres of tributary area. A typical computation is shown on Table 3. The results of this analysis are summarized in Table 4. This analysis was applied to specific

COMBINED SYSTEM TRIBUTARY AREA OF 1,000 ACRES[a]

Without Treatment Basin			With 0.4 Million Cubic Feet Treatment Basin								
Overflow To Bay Million Cubic Feet			Stored And Pumped To Treatment Plant Million Cubic Feet			Total To Treatment Plant Million Cubic Feet			Overflow To Bay Million Cubic Feet		
Total	Runoff	Sanitary	Total	Runoff	Sanitary	Total	Runoff	Sanitary	Total	Runoff	Sanitary
(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)	(21)	(22)
2.97	2.53	.44	.40	.34	.06	1.64	1.40	.24	2.57	2.19	.38
2.04	1.69	.35	.40	.33	.07	1.46	1.21	.25	1.64	1.36	.28
1.50	1.20	.30	.40	.32	.08	1.38	1.11	.27	1.10	.88	.22
1.24	.98	.26	.40	.32	.08	1.32	1.04	.28	.84	.66	.18
1.04	.80	.24	.40	.31	.09	1.28	.99	.29	.64	.49	.15
.86	.75	.21	.40	.30	.10	1.22	.92	.30	.46	.35	.11
.73	.54	.19	.40	.30	.10	1.18	.88	.30	.33	.24	.09
.65	.48	.17	.40	.30	.10	1.14	.84	.30	.25	.18	.07
.57	.41	.16	.40	.29	.11	1.12	.81	.31	.17	.12	.05
.52	.37	.15	.40	.29	.11	1.08	.78	.30	.12	.08	.04
.47	.33	.14	.40	.28	.12	1.06	.75	.31	.07	.05	.02
.42	.29	.13	.40	.28	.12	1.04	.73	.31	.02	.01	.01
.37	.25	.12	.37	.25	.12	.99	.68	.31	0	0	0
.33	.22	.11	.33	.22	.11	.93	.63	.30	0	0	0
.28	.19	.09	.28	.19	.09	.86	.57	.29	0	0	0
.24	.16	.08	.24	.16	.08	.78	.51	.27	0	0	0
.21	.14	.07	.21	.14	.07	.73	.47	.26	0	0	0
.17	.11	.06	.17	.11	.06	.67	.42	.25	0	0	0
.13	.08	.05	.13	.08	.05	.61	.37	.24	0	0	0
.10	.06	.04	.10	.06	.04	.56	.33	.23	0	0	0
.14	.08	.06	.14	.08	.06	2.32	1.23	1.09	0	0	0
0	0	0	0	0	0	1.38	.65	.73	0	0	0
0	0	0	0	0	0	1.53	.44	1.09	0	0	0
14.98	11.56	3.42	6.77	4.95	1.82	26.28	17.76	8.52	8.21	6.61	1.60
43.4%		2.56%				76.2%			23.8%		1.20%

(of Total Sanitary Flow in 5-month Season)

wetting. Runoff assumed at 40% of (Rainfall - 0.03 m.). Sanitary Flow assumed at 6,530
Flow in 5-month Season = 253 days x 0.872 = 133.5 mill cu ft.

areas, taking into account actual overflow outlet capacities. Retention basins were then sized to provide a volume of 400,000 cu ft per 1,000 acres, which resulted in a minimum of about 15 min displacement on the maximum flow capacity, considered adequate for chlorination contact. This relationship between tributary area and basin capacity was generally adopted, with some adjustments under special conditions. Fig. 3, from the New York City study, shows a typical general arrangement of basins and describes the suggested operating procedure.

One part of the New York City study involved the proposition of opening and maintaining four bathing beaches in Jamaica Bay. There are three sewage treatment plants in operation which maintain conditions satisfactory for bathing during prolonged dry periods, but the bacterial pollution from overflows is

such as to preclude the continuous use of beaches. It was estimated that the marginal bacterial pollution could be abated for about $40,000,000, of which about $23,000,000 was for changes and additions to the existing sewer systems and about $17,000,000 for the construction of seven overflow treatment facilities. The total combined sewer area tributary was about 15,700 acres and the cost for the treatment facilities was about $1,100 per acre. This is less than 7% of the amount that would probably be required to accomplish complete separation of sewage from storm water runoff.

TABLE 4.—SUMMARY OF BASIN REQUIREMENTS COMPUTATION

Volume of basin, in 100,000 cu ft per 1,000 acres (1)	Number of overflows received (2)	Number of overflows entirely contained (3)	Number of treated overflows to waterway (4)	Average interval between such overflows, in days (5)	Treated sewage lost through overflows, in percent (6)
2	25	8	17	9.0	1.8
4	25	13	12	12.7	1.2
8	25	19	6	25.5	0.6
12	25	21	4	38.2	0.4

CONCLUSIONS

Several pertinent conclusions may be summarized, as follows:

1. The prevalence of combined sewer systems in older cities requires consideration of the overflows resulting from rainstorms in procedures for pollution abatement.
2. Intercepting sewers with capacity for the dry weather flow and the first flushings from storm runoff will restrict the discharge of sewage through overflows to about 3% of the total sewage quantity. Little is gained by providing greater capacity.
3. With complete treatment of the intercepted flow, about 90% of the B.O.D. can be removed. The load discharged through overflows of about 30% of the effluent load, must be considered in evaluating the effects of sewage treatment on the waterway.
4. Complete separation by the construction of a new system of sanitary sewers would eliminate combined sewage overflows. This procedure, because of its cost, inconvenience, and time of accomplishment, must be considered as of limited application.
5. Retention basins for removal of floating solids and to provide chlorination contact can control bacterial pollution from the intermittent discharges of combined sewage overflows at an estimated cost of about $1,100 per acre of combined sewer tributary area. this procedure appears practical where the need for recreational use of the waterway warrants such expenditures.

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DISCUSSION

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WASTE TREATMENT AT THE SHIPPINGPORT REACTOR[a]

Discussion by Conrad P. Straub and Vincent J. Sodd

CONRAD P. STRAUB,[4] M. ASCE., and VINCENT J. SODD.[5]—The treatment and handling of radioactive waste materials from nuclear energy establishments is a subject of considerable interest to many sanitary engineers. The authors are to be complimented in adding specific information to the literature on this subject. For the first time, data are presented on the quantities of specific wastes produced by various segments of a nuclear power plant complex. Not only is information given on the kinds of wastes, but also on the sources of these waste materials. Data are also presented on tritium activity levels released to the environment.

In comparing estimated waste volumes and activity levels with actual quantities produced, the authors provide for subsequent design use a more adequate basis for the estimation of such radioactive and other waste materials. Attention is also called to the fact that as operations proceed, levels of radioactivity will change and the variety of radioactive materials produced may increase. In addition, it is recognized that non-radioactive wastes also occur in nuclear energy operations and that facilities for handling and treating these will have to be considered in the design of any works.

The Public Health Service has had the privilege of cooperating with the Shippingport Reactor people and has collected samples in the vicinity of the reactor site. Preoperational studies were carried out to determine existing levels of radioactivity in a variety of environmental media and were made to confirm studies carried out by the contractor-operator. With operation of the plant, emphasis was placed on the development of methods for the measurement of tritium in environmental samples, particularly in liquid wastes and in the receiving stream. Through the cooperation of plant personnel, samples from four locations at or in the vicinity of the site were submitted to our laboratories in Cincinnati. One of these, at Montgomery Dam, is located upstream of the site; the second, at Lock 7 in Midland, Pennsylvania, is located downstream. In addition to these two environmental samples, condenser coolant flow effluent and waste from a test tank have been submitted as indicators of the kinds of material produced on site and release following dilution into the Ohio River.

The analytical results obtained are summarized in Table 6 and show that the gross alpha and beta activity levels in the suspended and dissolved solids fractions were low during the periods of collection in 1959 and 1960. These data are more recent than those reported by the authors for the first 11 months of

[a] May, 1960 by J. R. LePointe, W. J. Hahn, and E. D. Harward, Jr.

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[5] Chemist, Methods Development, Radiological Health Research Activities, Div. of Radiological Health, Public Health Service, Robert A. Taft San. Engrg. Center, Cincinnati, Ohio.

TABLE 6.—RADIOACTIVITY DATA

Collection site (1)	Date (2)	Suspended Solids: Weight in, mg per l (3)	Suspended Solids: Beta Activity, $\pm 2\sigma$ $\mu\mu$c per l (4)	Suspended Solids: Alpha activity $\pm 2\sigma$ $\mu\mu$c per l (5)
Montgomery Dam, Ohio River Ohio view, Pa. (up river)	3/16/59	42.2	2.6 ± 3.4	1.0 ± 1.0
	7/10/59	22.0	8.9 ± 4.2	0.2 ± 0.6
	9/18/59	24.0	4.8 ± 5.4	0.0 ± 0.6
	6/16/60	32.6	0.0 ± 4.4	0.3 ± 0.7
Lock 7, Ohio River Midland, Pa. (down river)	3/16/59	80.4	13.2 ± 4.1	1.8 ± 1.2
	7/10/59	31.6	15.9 ± 4.5	0.0 ± 0.4
	9/18/59	19.0	0.0 ± 6.0	0.0 ± 0.6
	6/16/60	76.8	0.4 ± 5.6	0.6 ± 0.8
Condenser coolant flow Ohio River Shippingport, Pa. (Effluent from condensers)	3/16/59	65.0	13.2 ± 3.6	0.4 ± 1.0
	7/10/59	22.6	10.5 ± 4.2	0.2 ± 0.6
	9/18/59	38.0	1.6 ± 6.8	0.0 ± 0.6
	6/16/60	54.6	0.7 ± 4.9	0.4 ± 0.8
1A test tank (from 1D surge tank)	3/16/59	9.2	6200 ± 61	52 ± 2.6
	7/10/59	23.6	16380 ± 69	2.0 ± 1.0
	9/18/59	67.4	3217 ± 35	2.2 ± 1.0
	6/16/60	44.0	361 ± 12	1.0 ± 0.7

[a] The efficiency of counting has been increased from 1.61% to 3.98% by changes in

1958. An examination of the Ohio River data upstream and downstream of the site shows little difference in activity levels. (A word of caution regarding these data--some of the samples collected may have followed periods of plant shutdown and may not be representative of actual operating conditions. Results from continuous sampling would have been preferable to the grab sample results reported herein). The data reported for the in-plant samples show somewhat higher activity levels that are quite variable. Scintillation spectrometry gamma-ray scans made on the series of samples collected on June 16, 1960 showed no gamma-emitting nuclides in the Ohio River and condenser collant samples. The 1 A Test Tank sample showed the presence of Mn^{54}, Co^{60}, Cs^{134}, and Cs^{137}-Ba^{137m}.

The discharge criteria established by the Commonwealth of Pennsylvania permit a release of 10^{-8} μc per ml (10 $\mu\mu$c per liter) of gross activity in excess of the plant intake water from the Ohio River and 10 curies per day of tritium averaged over any consective 365-day period or 50 curries per day maximum. The differences in respective upstream and downstream levels of activity are small and within the criterion of 10 $\mu\mu$c per l. The tritium values reported upstream range from 0 to 2.5 $\mu\mu$c per ml, whereas the downstream values range from 1.4 to 10.3. These values may be compared with maximum permissible occupational concentration (168 hr week) of 0.03 μc per ml. (Reference is made to the maximum permissible concentration values as given in NBS Handbook 69 pending release of Radioactivity Concentration Guides by the Federal Radiation Council. A release by the Federal Radiation Council states: "No specific numerical recommendations for Radioactivity Concentration Guides are provided at this time. However, concentration guides now used by agencies appear appropriate on an interim basis. . .") The average permissible concentration level would be 1/30 of this value or 1000 $\mu\mu$c per ml. Thus, the highest concentration of 10.3 $\mu\mu$c per ml reported downstream is approximately 1/100 of the average permissible concentration. The in-plant tritium activity

TABLE 6.—*CONTINUED*

Dissolved Solids			Tritium	
Weight in, mg per l (6)	Beta Activity, $\pm 2\sigma$ $\mu\mu$c per l (7)	Alpha Activity $\pm 2\sigma$ $\mu\mu$c per l (8)	dpm per ml $\pm 2\sigma$ (9)	$\mu\mu$c per ml $\pm 2\sigma$ (10)
192.6	12.2 ± 3.8	0.6 ± 1.0	1.6 ± 14.0	0.7 ± 6.3
345.8	8.2 ± 6.7	0.6 ± 1.0	5.6 ± 14.1	2.5 ± 6.3
403.0	3.9 ± 9.1	0.0 ± 0.6	0.0 ± 14.1	0.0 ± 6.4
255.4	11.1 ± 6.6	0.5 ± 1.0	. . .	0.0 ± 3.5[a]
189.4	12.9 ± 4.0	2.0 ± 1.2	3.1 ± 14.0	1.4 ± 6.3
332.0	14.3 ± 5.1	0.2 ± 0.4	23.0 ± 14.4	10.3 ± 6.4
385.0	8.3 ± 10.3	0.0 ± 0.6	4.9 ± 14.3	2.2 ± 6.4
328.2	16.9 ± 7.2	1.0 ± 1.9	. . .	3.8 ± 3.3[a]
189.4	15.4 ± 4.0	0.0 ± 0.4	108.7 ± 15.5	49.0 ± 7.0
447.6	43.6 ± 7.3	0.2 ± 0.6	5.3 ± 12.0	2.4 ± 5.4
447.0	21.3 ± 10.8	0.0 ± 0.6	6.6 ± 14.1	3.0 ± 6.4
220.0	2.6 ± 4.8	0.2 ± 0.9	. . .	23.4 ± 3.3[a]
54.6	11,530 ± 83	262.9 ± 5.4	200,000 ± 400	90,100 ± 200
111.6	10,073 ± 83	0.2 ± 0.6	283,000 ± 300	127,500 ± 200
999.1	1,277 ± 32	0.0 ± 0.4	697.4 ± 15.1	314.1 ± 6.8
258.2	8,374 ± 59	0.0 ± 1.0	. . .	26,200 ± 120[a]

instrument operation.

levels were considerably higher than this (up to 127,500 $\mu\mu$c per ml), but with the dilution afforded by condenser cooling water and the flow in the Ohio River, activity levels are materially reduced (to the maximum level of 10.3 $\mu\mu$c per ml indicated). The nuclides contained in the 1A Test Tank for occupational MPC values (168 hr week) in water range from 9×10^{-5} to 10^{-3} μc per ml. The most hazardous of these had an average population permissible concentration in water of 300 times the present permissible release concentration of gross beta-gamma activity to the Ohio River.

The writers are happy to note that the authors report their releases not only in terms of the concentration, but also in terms of the total amount of activity released.

LIGHT CONVERSION EFFICIENCY OF ALGAE GROWN IN SEWAGE[a]

Discussion by Edward R. Hermann

EDWARD R. HERMANN,[15] M. ASCE.—Mr. Oswald's contribution to the understanding and measurement of stabilization processes in wastewaters containing commensal populations of algae and bacteria is of real significance. For cultures containing predominantly algal biota, Mr. Oswald's synoptic statement that engineering design of algal cultures for waste treatment or reclamation is dependent on the efficiency of algae to convert light energy to chemical energy holds true; this is with the provision that there be subsequent removal of the algal cell material formed along with its utilization in some oxidative process with release of the stored energy as in combustion, foodstuff metabolism, or anaerobic sludge digestion. In waste treatment practice the predominant species in waste stabilization ponds are frequently bacterial. For the broad spectrum of algal-bacterial commensal systems that may be classified as waste stabilization ponds, some consideration must be given to the possibility that light conversion efficiency in some ponds can be dependent on the presence in sufficient quantity of certain nutrient materials, the supply of which depends in turn on the rate of bacterial oxidation.

Analysis of Results.—The results of Mr. Oswald's studies on light conversion efficiency of algae grown in sewage are presented mainly as empirical mathematical equations and corresponding graphs showing the influence of various environmental factors. Reference to Table 2 indicates that the average experimental conditions for cultures of Chlorella pyrenoidosa were comparable in columns b, f, and g with the exception that a different independent variable was chosen in each case, such as detention period, BOD, and temperature. Thus, the light efficiency expression relative to detention period (Eq. 8), may be equated to the light efficiency expression relative to temperature (Eq. 13), to yield the detention-temperature relationship,

$$\ln D = 6.06 - 1.66 \ln T \quad \ldots\ldots\ldots\ldots \quad (17)$$

A plot of Eq. 17 is shown in Fig. 13, with the useful portion of the curve probably lying between 1.5 and 10 days of detention. For comparison, Hermann's adaptation of the Arrhenius reaction rate equation[16] may be used to develop the two curves shown.

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[a] July, 1960, by William J. Oswald.

[15] Health Engr., Medical Div., Humble Oil & Refining Co., Baytown, Tex.

[16] "Development of Design Criteria for Waste Stabilization Ponds," by E. R. Hermann, Dissertation, University of Texas, University Microfilms, Ann Arbor, Mich., 1957, p. 117.

Let the reaction time ratio $\frac{t}{t_o} = \frac{D}{D_o}$, the detention time ratio, then

$$\frac{D}{D_o} = e^{c(T_o - T)} = \theta^{(T_o - T)} \quad \ldots\ldots\ldots\ldots \quad (18)$$

If the optimum detention D_o is 3.25 days, the optimum temperature T_o is 35 C, and $e^c = e^{0.0693} = \theta = 1.072$ making the slope of an Arrhenius curve follow the van't Hoff rule-of-thumb that chemical reaction rates double for each 10 C rise in temperature, we obtain

$$D = 3.25 \times 1.072^{(35-T)} \quad \ldots\ldots\ldots\ldots \quad (19)$$

that agrees with the theoretical and experimental findings reported by Hermann and Gloyna for predominantly bacterial stabilization ponds.[17,18] However, if an optimum temperature T_o of 20 C is used in the van't Hoff-Arrhenius equation for the same detention D_o we obtain the isoline

$$D = 3.25 \times 1.072^{(20-T)} \quad \ldots\ldots\ldots\ldots \quad (20)$$

that obviously coincides quite well with Oswald's findings for predominantly algal cultures. Compare curves from Eqs. 17 and 20 in Fig. 13.

Similar equating of the light conversion efficiency expression $F = 1.3(\ln L - 3.5)$ in which L is 5 day 20 C BOD to the temperature dependent expression $F = 3.48(\ln T - 1.85)$ provides a BOD-temperature relation

$$\ln L = 2.68 \ln T - 1.46 \quad \ldots\ldots\ldots\ldots \quad (21)$$

Due to the direct relationships between reaction time, detention period (residence time), and volume of a reaction vessel, BOD loading of a stabilization pond is equal to L/D, and from Eq. 21 the following loading expression is obtained:

$$\ln \frac{L}{D} = 2.68 \ln T - 1.46 - \ln D \quad \ldots\ldots\ldots \quad (22)$$

that reduces to

$$\ln(\text{BOD loading}) = 2.68 \ln T - 0.28 \quad \ldots\ldots\ldots \quad (23)$$

for a detention period of 3.25 days. In this case, BOD loading is in milligrams per liter per day, and temperature is in degrees centigrade. Graphic forms of Eqs. 21 and 23 appear in Fig. 14. In accordance with the findings presented by Oswald the valid portions of these two curves lie between 7 C and 20 C. For comparison, two van't Hoff-Arrhenius isolines are shown in Fig. 14. The upper one corresponds to

$$\text{BOD loading} = 566 \times 1.072^{(T-35)} \quad \ldots\ldots\ldots \quad (24)$$

that represents a predominantly bacterial stabilization pond operated at maximum work efficiency but capable of providing only 50% BOD removal. The low-

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17 "Waste Stabilization Ponds, Part I. Experimental Investigations," by E. R. Hermann and E. F. Gloyna, Sewage and Industrial Wastes, Vol. 30, No. 8, 1958, p. 511.

18 "Waste Stabilization Ponds, Part III. Formulation of Design Equations," by E. R. Hermann and E. F. Gloyna, Sewage and Industrial Wastes, Vol. 30, No. 8, 1958, p. 963.

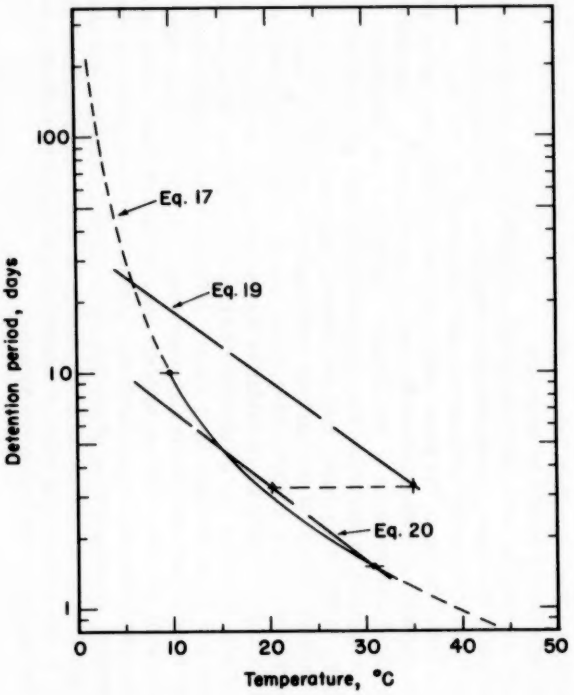

FIG. 13.—COMPARISON OF DETENTION-TEMPERATURE CURVES FOR STABILIZATION POND CULTURES.

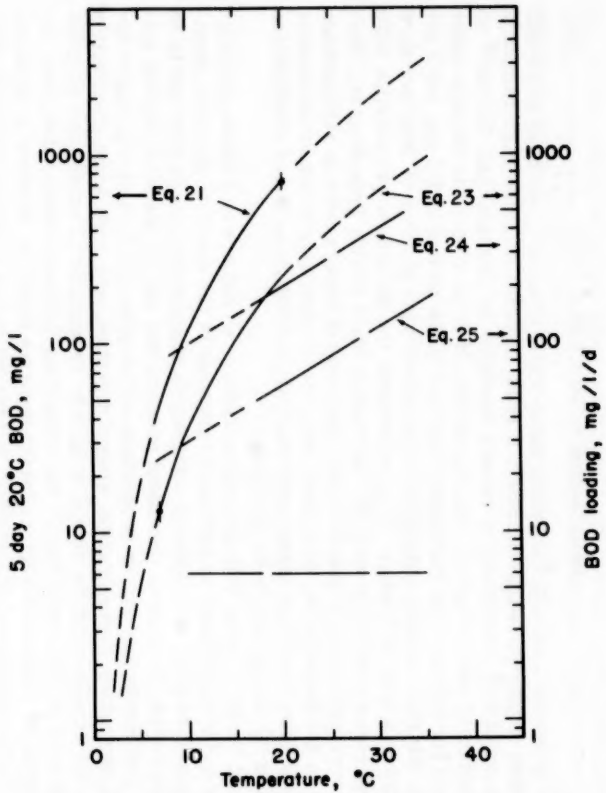

FIG. 14.—COMPARISON OF BOD LOADING-TEMPERATURE CURVES FOR STABILIZATION POND CULTURES.

er curve is given by

$$\text{BOD loading} = 170 \times 1.072^{(T-35)} \quad \ldots\ldots\ldots \quad (25)$$

that represents a similar biological waste-water reactor operated at somewhat less than maximum work efficiency. It does, however, provide BOD removals in excess of 85%, according to results reported by Hermann and Gloyna[18] on 18 laboratory model reactors run for periods of from 30 days to 70 days under various conditions. The horizontal line in Fig. 14 plotted at 6.1 mg per l per day is the BOD loading equivalent of an application of 50 lb of BOD per acre per day to a pond 3 ft deep. This represents the maximum permissible BOD loading recommended by some of our leading State Health Departments. This last curve erroneously indicates that treatment of wastewaters in stabilization ponds is not temperature dependent and, clearly shows, from the broad considerations presented, that engineered exploitation of the potentials of stabilization ponds is far behind available knowledge.

Most readers, along with the author and this writer are well aware, that rigorous and elegant cause and effect development of the complex physical, chemical, and biological mechanisms obtaining in stabilization ponds have yet to be accomplished. In a waste treatment process that can be made to provide primary sedimentation, oxygen production, satisfaction of biochemical oxygen demand, secondary sedimentation, sludge digestion, and even some disinfection all in one simple reaction vessel it is only reasonable to expect the ultimate in obtaining an understanding of the underlying processes and subsequent development of rational design criteria; theories based on Einstein's classical work on photochemical equivalence, determinations of quantum yield with resolution of the discrepancies between the values obtained by various authorities such as Warburg and Negelein and Emerson and Lewis, Camp's theory of sedimentation, the Beer-Lambert law of light absorption, and van't Hoff-Arrhenius reaction rate theory should be included.

Though sometimes used interchangeably, symbiosis and commensalism are not technically the same. Symbiosis may be defined as the consortism or union for life of two dissimilar organisms, each necessary to the other, whereas, commensalism (eating at the same table) denotes an organism living with another for support or mutual advantage but not as a parasite. The relationship between algae and bacteria in stabilization ponds are not symbiotic; in fact, for certain species, evidence has been presented that they are antibiotic. Commensalism, on the other hand, may be induced and maintained at any relative balance through control of the various environmental factors by man. The algae/bacteria ratio in a culture determines, among other things, whether it is best suited to functioning as an oxidative waste treatment device or as a liquid photosynthetic farm for the production of algal cells that can be separated and recovered for their fuel and food value. Although waste stabilization ponds should be considered algal-bacterial commensal systems, the idea that the interrelationship between various species may be synergistic under properly controlled conditions and algal-bacterial population ratios presents itself for consideration. Demonstration of whether or not true synergism may exist and of how much work may be obtained in excess of that available from algal or bacterial species alone will require fundamental and applied research investigations far beyond those presented to date.

Despite a lack of complete scientific understanding of waste stabilization pond mechanisms, the engineering science and art is sufficiently developed to enable practicing engineers to select and design such ponds as their treatment method of choice.[18,19,20,21]

19 "An Evaluation of Stabilization Pond Literature," by G. P. Fitzgerald and G. A. Rohlich, Sewage and Industrial Wastes, Vol. 30, No. 10, 1958, p. 1213.

20 "Algae in Waste Treatment," by W. J. Oswald, H. B. Gotaas, C. G. Golueke, and W. R. Kellen, Sewage and Industrial Wastes, Vol. 29, No. 4, 1957, p. 437.

21 "Sewage Treatment Construction Costs," by P. P. Rowan, K. H. Jenkins, and D. W. Butler, Sewage and Industrial Wastes, Vol. 32, No. 6, 1960, p. 594.

SOLUBILITY OF ATMOSPHERIC OXYGEN IN WATER[a]

Discussion by J. Carrell Morris, Werner Stumm, and Hend A. Galal

J. CARRELL MORRIS,[10] WERNER STUMM,[11] M. ASCE, and HEND A. GALAL.[12]—It had not been planned to publish the studies on oxygen solubility carried out at Harvard for the USPHS by Morris, Stumm, and Galal[13] at this time for three reasons: additional measurements below 5°C and above 30°C were required to cover fully the temperature range of interest; it was felt that more precise results could be obtained with slightly redesigned apparatus; and it was hoped that the discrepancy with Truesdale's data could be resolved before publication.

The appearance of the data obtained at TVA and the good agreement of these data with those obtained at Harvard have decreased the feeling of need for immediate, additional work. Consequently, it seems desirable to record some of the details of the Harvard experiments that may be of general interest, plus the saturation values that were obtained.

The apparatus used for saturation of distilled water with air at constant temperature and pressure is shown in Fig. 3. Normal air, freed from CO_2 and saturated with water vapor by passage through appropriate wash bottles was pumped, with a small vibrating pump at a pressure slightly greater than atmospheric, over the surface of the slowly stirred (3 rpm) distilled water in the reaction vessel and then discharged to the atmosphere through a mineral-oil column. The height of the mineral-oil column was automatically adjusted to compensate for changes in atmospheric pressure so that constant pressure within a few tenths of a milimeter of mercury was maintained in the reaction vessel. Any changes in pressure in the reaction vessel caused by a change in the back atmospheric pressure on the oil column resulted in an unbalance of the levels in the differential manometer and establishment of electrical contact through the liquid in one of the arms of the manometer, depending on the direction of the pressure shift. The electrical contact activated a relay causing a reversing motor to operate and shift the height of the oil column in the proper direction to counterbalance the pressure change. The differential manometer was filled with copper sulfate solution and equipped with copper contacts to avoid electrochemical discharge of gas.

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[a] July, 1960, Twenty-ninth Progress Report of the Committee on San. Engrg.

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[13] Final Report by J. Carrell Morris under contract SAph 69705 between U. S. Pub. Health Service, Dept. of Health, Educ., and Welfare, and Harvard Univ., January 31, 1959.

Temperatures of the reaction vessel, wash bottles, and ballast bulb were kept constant within 0.03°C by immersing them in a large thermostatted waterbath.

About three days was required to reach saturation within analytical error in this apparatus. After such an elapsed time and for several days thereafter samples were withdrawn from the vessels and concentrations of dissolved oxygen were determined by virtually the same modification of the Winkler method as that used by Elmore and Hayes in the TVA study.

The apparatus used for the manometric determinations is shown schematically in Fig. 4. The measurements were made by bringing pure gaseous oxygen at a known pressure into contact with a known volume of deaerated, distilled water in a closed system. As equilibrium was established gradually during slow agitation (rocking), the oxygen absorbed by the water was replaced from a gas buret to restore the pressure to its initial value. The solubility is computed from the buret during the equilibration period.

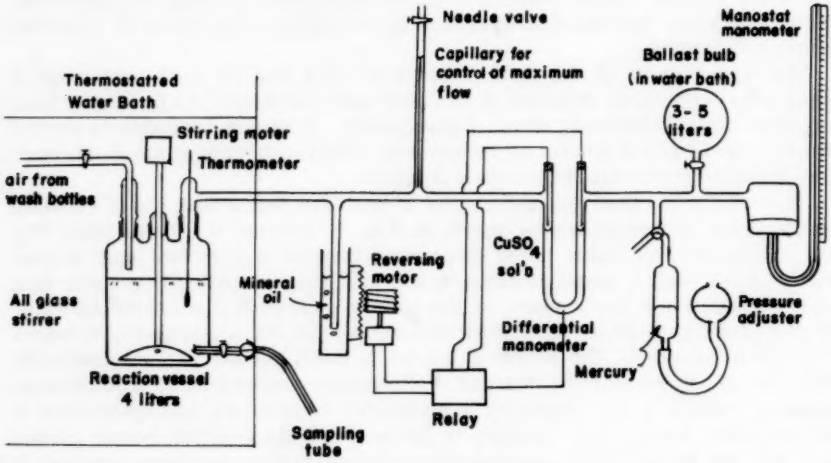

FIG. 3.—APPARATUS FOR OBTAINING SATURATION OF WATER WITH AIR AT CONSTANT PRESSURE

Bulbs A and B, with their associated tubing, were used for deaeration of the distilled water by vacuum distillation and freezing. The deaerated water was then transferred to the reaction vessel, E, filling it completely. The volume of water contained in S, including that in the bore of the stopcocks, a and b, was determined by weight calibration before it was attached to the main part of the apparatus. The liquid was then brought into contact with oxygen at a known pressure contained in pipet, n, and allowed to equilibrate with it. The oxygen that dissolved was replaced periodically from buret B. Gas vessel, n, was made about 1/10 the size of S to accentuate the pressure drop caused by the solution of a small amount of oxygen. Because the distribution coefficient for oxygen is about 0.03 between water and gas phase, the total pressure change expected without replacement of oxygen would have been about 0.3 times the

initial oxygen pressure of about 150 to 300 mm of Hg for the total pressures used. Because pressure difference differences of .1 mm could be read easily, the potential precision was of the order of 0.1%.

Pressure differences were determined with the manometer, U, formed of two pieces of precision-bore capillary tubing from the same length fused to a lower-section of 8-mm tubing. The lower u-section was filled within about one mm of the capillary tubes with purified mercury; above this, in each arm of the tube, was placed a sufficient amount of water to rise a few centimeters into the capillary. This design of manometer had three advantages: (1) for small pressure differences it had the sensitivity of a water manometer; (2) larger pressure differences caused mercury to enter one capillary or the other

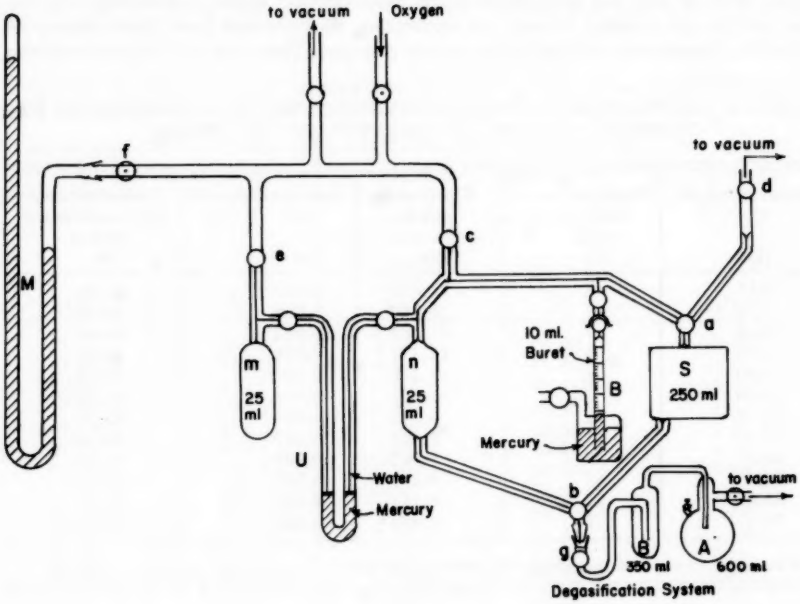

FIG. 4.—APPARATUS FOR MANOMETRIC DETERMINATION OF OXYGEN SOLUBILITY

to reduce the sensitivity and thus, the required length of the manometer arms; (3) only about 0.3 ml of water was exposed to the oxygen in n or about 0.1% of the volume of S. The reference side of the manometer was connected with a ballast pipet, m, of the same shape and volume as n; this was filled with oxygen at the same initial pressure as in n at the start of the experiment.

Equilibrium was reached with this system in about one and one-half days, as shown by the constancy of the pressure. In order to be sure that equilibrium had been attained, the oxygen pressure was raised somewhat by supplying additional gas from the buret and held at the higher value for some time. Then the buret level was returned to its former value, and return to the original pressure was observed.

Saturation values for dissolved oxygen obtained by the first method are given in Table 4; those obtained by the manometric method are given in Table 5.

In spite of the excellent precision of the data obtained by the TVA group and their gratifying concordance with our results, there still remain some questions about the accuracy of their data and of the computed saturation values in Table 2, in which no weight has been given to other experimental data. There are two omissions in the description of the experimental details of the studies by Elmore and Hayes: (1) There is no indication of the way in which they were assured that the air being equilibrated with the water was saturated with water vapor. It is likely that saturation with water vapor was achieved at least for the thin layer of contact between gas and water, but with an air flow of 250 ml per min, some unsaturation appears possible. Moreover, if the air coming in was not saturated, there would have been evaporation with consequent cooling at the water surface. Then the equilibrium estab-

TABLE 4.—SATURATION VALUES FOR OXYGEN IN WATER AS DETERMINED BY CHEMICAL ANALYSIS OF AIR-SATURATED SOLUTIONS

Temperature, in °C (1)	Number of tests made (2)	C_s, in mg per l (3)	Standard deviation (4)	Bunsen absorption coefficient 1000 x (5)
5.14	8	12.833	0.021	43.33
7.24	7	12.050	0.029	40.74
9.53	5	11.542	0.032	39.08
9.58	5	11.371	0.022	38.51
9.93	4	11.319	0.030	38.34
14.76	7	10.104	0.015	34.38
18.16	11	9.475	0.037	32.38
18.50	11	9.404	0.063	32.15
19.41	12	9.265	0.028	31.71
23.47	17	8.567	0.052	29.52
25.80	12	8.141	0.028	28.17
29.10	5	(7813)[a]	0.022	(27.23)[a]

[a] Results somewhat uncertain because of possible error in manometer reading.

lished, that must correspond to the conditions at the surface, would have been for a somewhat different temperature than that measured in the bulk water. (2) There is no mention of correction of measured barometric pressures to standard conditions. These corrections may amount to as much as 0.5%. If they have not been made, it would account for the curious fact that near 30°C the values obtained by Elmore and Hayes are lower than those of the other investigators cited. The location of the barometer is also important, for significant differences in pressure have been noted for different rooms in the same building, especially when air-conditioning equipment is in use.

It may be that all of these factors have been taken into account and have just not been mentioned. However, they are indicative of the precautions that must have been specifically controlled before any set of saturation values can be accepted as definitive.

Some observations on the form of the equation used for computation of the smoothed saturation values as a function of temperature also appear per-

tinent. Although the power-series form will reproduce any number of joints to any desired degree of precision, provided a sufficient number of terms is used, it would seem more desirable to use a type of equation with some theoretical basis when the distinct points are relatively few, and when the correct shape of curve near the ends of the range of experimental values is important. In the present instance, the following features may be noted: (1) Four adjustable constants have been used to determine a curve for seven points. With four constants available for four points, the fit would have been perfect. Thus, only three of the points are independent tests of the goodness of fit. (2) In the important region between 25 and 30°C, only the point at 29° is available for computing the shape or slope of the curve. Because this is the point that is most at variance from other determinations, the reliability of a purely impirical fitting is relatively low for this region of the saturation curve. Even-

TABLE 5.—SATURATION VALUES FOR OXYGEN IN WATER AS DETERMINED BY MANOMETRIC MEASUREMENTS

Temperature, in °C (1)	Total pressure, in mm Hg at 0°C (2)	ml oxygen absorbed in 249.8 at pressure and temperature of experiment (3)	Bunsen absorption coefficient 1000 (4)	C_s, in mg 0_2 per l (5)
11.47	802.0	9.60	36.88	10.89
14.54	628.4	9.05	34.40	10.13
15.00	657.2	9.06	34.38	10.12
15.00	643.2	8.94	33.93	9.99
17.03	674.8	8.77	33.05	9.70
22.79	649.9	7.98	29.49	8.59
22.79	765.2	7.94	29.34	8.54
22.79	799.0	8.00	22.56	8.61
22.79	581.4	7.925	29.28	8.53
22.79	634.0	7.94	29.34	8.54
26.97	791.8	7.54	27.47	7.93
26.98	761.0	7.565	27.56	7.95
29.96	780.0	7.43	26.80	7.69

tually, accuarate measurements should be at higher temperature, up to perhaps 50°C, to establish the shape of the fitted curve in the 25 to 30° range with greater confidence. (3) The situation is somewhat the same at the low-temperature end of the range, but unfortunately experimental results cannot be obtained at temperatures less thean 0°C to fix the slope at thisend of the curve. However, efforts should be made to obtain precise experimental values at a temperature not exceeding 0.5° C so that the extrapolation necessary to obtain a value at 0°C is as short as possible.

Because of these problems, it is felt that the formula used for interpolation should take advantage of the thermodynamic relation that the differential logarithmic change of solubility was reciprocal Kelvin temperature is proportional to the enthalpy change of solution in accordance with the equation.

$$d \ln \frac{S}{d} (1/t) = \frac{\Delta H}{R} \quad \ldots\ldots\ldots\ldots\ldots\ldots (4)$$

Although the enthalpy change, ΔH, is not independent of temperature, it normally varies slowly enough so that use of log S and $1/T$ as variables, rather than S and T, provides a nearly linear relationship and thus, a more satisfactory interpolative equation for primary preparation of tables. One form of the integrated expression corresponding to the previous equation is

$$T \log S = b + aT \quad \ldots\ldots\ldots\ldots\ldots\ldots (5)$$

so that a plotting of T log S as a function of T will give nearly a straight line, and the right-hand side can be expanded readily to power-series form as needed.

Also this, or any interpolative scheme, should be carried out with the solubility expressed in terms of Bunsen coefficients rather than the saturation values ordinarily used in water work. The latter refer to a non-constant standard pressure of oxygen, because of the changing vapor pressure of water with temperature. This complicates the temperature dependence of the solubility coefficient so that it cannot be mathematically analyzed as simple as that of the Bunsen coefficient. (It may be noted that any equation for the solubility coefficient as a function of temperature should give a value of zero for the solubility at 100°C, at which the standard pressure is entirely water vapor; by the equation given in the Committee Report a solubility of zero near 66°C is computed.)

These comments should not be taken as criticisms of the excellent work of Elmore and Hayes; rather they are recommendations for methods to be used in computing a definitive set of values for the solubility of oxygen in water when reliable and consistent data of sufficient range are available.

It must be appreciated that accurate determination of saturation values for oxygen in water is much more of a problem than it seems on first investigation. The recent investigations indicate that a high degree of reproducibility of analyses for dissolved oxygen in a single sample is readily attained, but that production of uniformly saturated solutions is difficult to achieve even with eleborate precautions and safeguards.

What this means, in practice, is that values for the absolute percentage saturation with dissolved oxygen of any sample cannot be given meaningfully to better than 1%; 1/10% of saturation are currently not significant. On the other hand, if precise analytical techniques are followed and the same base saturation values are used, differences of some tenths of a percent in saturation values may be significant.

ERRATA

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p. 134. In the last line change "Fig. 5" to "Fig. 6."

p. 137. In line 16, change "Fig. 6" to "Fig. 5."

p. 143. In line 18 change "coil" to "soil." In the second line from the bottom, change "bases" to "gases."

p. 147. In Reference 6 change "Macon" to "Mason."

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c. Discussion of several papers, grouped by divisions.

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